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METHODS AND APPLICATIONS OF ACOUSTIC EMISSION. COMPARATIVE ANALYSIS

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1. Some historical data

Acoustic signals which accompany internal changes of the structure of a continuous medium have been observed for centuries, and where often utilized as warning signals of oncoming catastrophes. These signals provoked also an interest as indicators of homogeneity and strength of material. First scientific concern for this kind of acoustic phenomena dates from the third decade of the twentieth century [1], and refers to "micro-seismic" signals. Further investigations [2] proved that the micro-seismic signals precede the mining catastrophes. Still the level of electronics of that time precluded an effective separation of the signals from the background noise, and measurement of the parameters of these signals. The research on acoustic phenomena in metals was undertaken at the beginning of the fifties, and resulted in discovering of (among other things) the so called Kaiser effect [3]. It was not, however, before the end of the fifties that the investigations of acoustic signals in different media developed on greater scale; they were first of all concentrated on the ones that appear in metals, as a result of mechanical loads.

Since 1962 (symposium at San Antonio) [4] the investigation of materials on the ground of acoustic signals has been presented at the scientific conferences on non-destructive testing of materials. In those days the term "acoustic emission" (abbreviation "AE") began being commonly used, displacing such terms as "stress wave emission", or "materials sounds". This term is not entirely exact, in as much as it comprises a wide band of frequencies: from infrasound to ultrasound. The acoustic emission is generally defined as a phenomenon based on the appearance of the elastic waves inside, or on the surface of a continuous medium. This term is often reduced to the phenomenon of the appearance of elastic waves as the result of a local, dynamic variation of the structure of the medium. It is not entirely well-grounded however, because also the acoustic signals in physical-chemical processes, for example during chemical reactions in liquids, should be regarded as the acoustic emission.

The essential development of applications of AE dates from the second half of the sixties. It could take place, first of all, due to the extension of the range of AE measurements to high frequencies, up to 30 MHz [5]. The application of computer technology in the last decade opened new possibilities of selection of AE signals, and determination of their parameters. At the same time the theoretical and experimental work has been conducted, aimed at interpreting the mechanism of creation of the AE signals. For instance, models of stimulation of the vibration of crystal lattice by a group of dislocations [6], and also a model based on the classical fracture theory, have been elaborated. Many research works from that period concerned the interrelation between the velocity of micro-cracks development, and the acoustic emission in brittle and semi-brittle materials [8]. As before, great attention was paid to the acoustic signals generated during rock mass motions, finding analogies between AE signals and the sounds that precede earthquake [9].

After specimen testings, evaluations of complete technical objects by means the AE method have appeared. The control of shielding of atomic reactors [10], degree of fatigue of aircraft parts [11], large-scale constructions (such as water dams [12]) may be mentioned here. Another direction of application is the control of technological processes, especially welding [13].

Further historical data will be quoted later on, when different applications of the AE methods will be discussed.

In Poland, the first works to master the AE measurements techniques date from the beginning of the seventies; at that time the first attempts of technical applications were made. The references to these works will be specified further, in connection with the analyzis of separate topics.

The real development of scientific and technical activities in the field of AE in Poland dates from the beginning of the eighties. They were carried out first within the so-called key projects, and since 1985 within the Central Project of Fundamental Research (CPBP No. 02.03) [14], that enabled better financing and coordination in the whole country. The national reporting Symposia, which were held by the end of each year, offered a good occasion to exchange of the experiences, and to assess the research progress. As the consequence of the economic transition, which recently took place in Poland, the system of central projects has been terminated. Nevertheless, numerous research projects concerning acoustic emission have been still centrally financed by a system of grants. The work initiated in the eighties has been continued and developed. The exchange of experience is now facilitated by organizing occasional symposia.

It is difficult to list all scientific institutions which deal with the AE phenomenon and its application; here only the ones are mentioned which have participated in the previous Central Project and are still continuing their work on AE; they are arranged according to the order of their consideration in this work (the range of applications being enclosed in brackets). They are as follows:

— Institute of Fundamental Technological Research of the Polish Academy of Sciences — Warszawa (metals, ceramics, rocks, instrumentation),

— Institute of Fundamental Metallurgy of the Polish Academy of Sciences — Kraków (metals),
— Institute of Inorganic Technology of the Warsaw Technical University — Warszawa (ceramics, technology),
— Institute of Physics of the Silesian Technical University — Gliwice (mining, superconductors),
— Institute of Fundamentals of Electronic and Electrotechnic of the Wrocław Technical University (superconductors),
— Institute of Building Engineering of the Wrocław Technical University — Wrocław (concretes, constructions),
— Department of High Pressures of the Polish Academy of Sciences — Warszawa (powdered materials, reference sources),
— Institute of Wood Technology of the Agricultural Academy — Poznań (wood technology),
— Institute of Mechanics of the Technical University — Lublin (soils),
— Institute of Building Engineering of the Technical University of Swiętokrzyskie Mountains — Kielce (rods),
— Institute of Applied Mechanics of the Technical University of Swiętokrzyskie Mountains — Kielce (composites),
— Institute of Applied Mechanics of the Technical University — Poznań (machinery parts),
— Institute of Vibroacoustics of the Academy of Mining and Metallurgy — Kraków (machinery parts),
— Institute of Electrotechnics of Engineering College — Opole (welding, electrical power devices),
— Institute of Chemical Analysis of the Warsaw University (chemical processes),
— Institute of Electrotechnics — Warszawa (partial discharges),
— Otolaryngological Clinic of the Medical Academy — Warszawa (oto-emission).

2. Classification of AE sources and applications

The appearance of AE in materials and objects is of very miscellaneous origins, and often a few different factors play simultaneously their roles in the process of the AE generation; nevertheless, certain classification would be useful for further considerations. The following classification, in accordance with the physical processes being the source of AE, will be assumed:

(1) Motions of the lattice imperfections in metals. These are mainly motions of dislocations and groups of vacancies, as well as transitions of atoms between different energy levels.

(2) Formation and propagation of micro-cracks, which may appear both in metals and ceramics.

(3) Creation and shape transformations of local material flaws, having for example the form of micro-cracks or pores.

(4) Mutual displacements of the layers of a medium, which take place, for instance, in rock masses.
(5) Reconstruction of the microstructure of a medium, relevant for instance to phase transitions or heat treatment.
(6) Chemical reactions, accompanied by local variations inside the medium, e.g. gas bubbling.
(7) Local motions of a gas medium. These may be caused, for instance, by electric discharges. It is however disputable if this kind of phenomena might be classified as the AE.

Another classification may be introduced by taking as a basis the kind of medium or object in which AE appears; this classification is almost identical with the classification according to the applications, being however not entirely coherent. We shall remain at this classification after all, mainly because of the fact that the activities of research laboratories may be divided in accordance with it. Let us assume the following division of the media, or the objects in which AE appears:
(1) Materials of plastic properties, metals are included here.
(2) Brittle materials, mainly ceramics.
(3) Materials which are macroscopically heterogenous, such as wood, concretes, composites.
(4) Geological layers; this group comprises rocks and soils.
(5) Machinery, and civil engineering objects, as well as their components, for example high pressure vessels, dams.
(6) Physical-chemical processes, mainly such as chemical reactions, incomplete electric discharges.
(7) Biological processes; it is a new, separate domain of the AE investigations, initiated by the oto-acoustic research of AE signals, taking part in the hearing process.

3. AE signals and source-receiver path

Acoustic emission appears usually inside the tested object. Before AE signal reaches the receiver on the surface of the object, it is subject to the attenuation and multiple reflections. Because of this, the absolute measuring of the intensity of the AE signals may be carried out only exceptionally. Usually AE signals versus time are measured in relative units, based on the receiver readings.

Taking into account the general character of the time changes, the following kinds of AE may be distinguished:
(a) Continuous emission, in which separate pulses merge, because their growth and collapse times are greater than the pauses between them;
(b) Burst emission which is characterized by the occurrence of groups of strong, distinctly discernable pulses.

Together with the development of the AE methods, a range of descriptors to characterize the AE signal have been introduced, they may be divided into three groups.

(1) The descriptors that characterize the time changes of the signal, comprising:
— sum of counts N, being the sum of the AE pulses which exceed an assumed discrimination level during a measuring period,
— count rate, which is the sum of pulses exceeding the discrimination level in time unit dN/dt,
— event, being an envelope of a sequence of pulses which exceed an assumed discrimination level.

The sum of events and event rate are suitably characterized.

On the basis of a closer analysis of the time changes, the following terms may also be defined:
— region of pulses, which have exceeded a discrimination level in a time unit,
— discrimination level, by which a specified number of crossings with depended curve take place,
— comparison of the count rate during successive observations.

(2) Shape of the pulse. The attempts of classification of the shapes of single pulses was undertaken [11]. Approximately the two basic shapes may be distinguished: relaxative and accelerative.

(3) Descriptors which describe the energy of signal:
— Root mean square RMS. This value relates to the voltage of an electric signal within the time T:

$$V_{\mathrm{RMS}} = \sqrt{\frac{1}{T} \int_{0}^{T} u^2(t)\ dt}\,. \tag{1}$$

— Distribution of the energy in the spectrum, defined as the share of the signal energy that belongs to the given frequency band.
— The mean energy of a single pulse, measured directly by a suitable electronic gauge, or defined as:

$$\frac{V_{\mathrm{RMS}}\, T}{N}. \tag{2}$$

For the purpose of measuring the AE signals it is essential to determine a general relationship between the electric parameters at the output of a measuring transducer: voltage $v(t)$, and current $i(t)$, and the mechanical factors on the surface of the tested object, which is in an undisturbed state. These are the displacements $\| u_0(x,t) \|$, and the force acting upon the unit of surface $\| f_0(x,t) \|$. Both the values are tensors. In an ideal example the following relationship might be written

$$\begin{Bmatrix} \| u_0(x,t) \| \\ \| f_0(x,t) \| \end{Bmatrix} \rightarrow \begin{Bmatrix} i(t) \\ v(t) \end{Bmatrix}.$$

When measurements are considered, however, it is necessary to take certain simplifying assumptions.

(1) Loading of the object by the transducer can be neglected; therefore $u_0(x,t) = u(x,t), f_0(x,t) = f(x,t)$, where u and f are displacement and force on the transducer.

(2) Values $\| u \|$, $\| f \|$ are the tensors, with components of different vibration modes. It is not possible to realize a measurement of the whole tensor by scalar values, therefore it has been assumed that the separate modes are not mutually associated at the place of measurement, and that the transducer measures the values u and f of only one mode. Then the values may be regarded as scalars.

(3) In majority of cases fields u and f changes smoothly together with the change of x, and it may be assumed that they remain equal on the whole surface of the transducer, what enables elimination of the coordinate x. It means that the following relationship can be admitted:

$$\begin{Bmatrix} u(f) \\ f(T) \end{Bmatrix} \to \begin{Bmatrix} v(f) \\ i(t) \end{Bmatrix}.$$

(4) It has been assumed that the proportionally exists between the mechanical and electrical values; that is to say, the system is linear. In a general case the response of the system has a form of a square matrix T_{ij}. To perform the measurement properly, stability of parameters of the mechanical configuration (impedance of the transition object-transducer), and the electrical parameters (input impedance of the preamplifier) is necessary. When assuming it, it is sufficient to determine of the relation between two values, for instance v and f, and the matrix T_{ij} reduces to one coefficient T. Then

$$v = T u.$$

For the purpose of AE measurements, determination of the distribution of the amplitudes of the signals received is essential. For continuous AE a Gauss distribution of amplitudes, stationary in time, may be accepted, the counts rate n being

$$n(x_0) = \int_{x_0}^{\infty} dx \int_{-\infty}^{0} -\ddot{x}\, p(x, \dot{x}, \ddot{x})_{x=0}\, dx, \tag{3}$$

i.e. the function of joint probability of displacement x, velocity $\dot{x}$, and acceleration $\ddot{x}$.

In case of a narrow transfer band the Rayleigh distribution is appropriate. The detailed calculations of the intermediate distributions may be found in paper [15]. In case of the burst emission, a single impulse produces an attenuated sine curve at the output. When the discrimination level equals x_0, the number of pulses received at the initial pulse (event) of amplitude x_i equals:

$$n = \frac{\omega_0}{2\pi\alpha} \ln \frac{x_i}{x_0}, \tag{4}$$

where: α — attenuation coefficient for a sequence of pulses.

If it is assumed that the amplitudes of events form the Rayleigh distribution, it will be possible to state that the events rate equals

$$n_e(x_i) = \left(\frac{n'_e x_i}{\xi^2}\right) \exp\left(-\frac{x_i^2}{2\xi^2}\right), \tag{5}$$

where: n'_e — total events rate of different amplitudes, ξ — the value of x_i for maximum of n_e.

The shape of the spectrum of AE signal depends on several factors. In the general case, when the signal appears as the result of vibration of a group of elements of a medium which are of different relaxation times τ and function $F(\tau)$, the spectrum is given by the relationship:

$$G(\omega) = 4 \int_0^\infty \frac{\tau^{-1}}{\tau^{-2}-\omega^2} F(\tau)\, d\tau, \tag{6}$$

where: $F(\tau) = \frac{kT}{\tau} F(E)$, E — activation energy, k — Boltzmann constant.

For example, if $F(E)$ = const

$$G(\omega) = 1/\omega, \tag{7}$$

if $F(E)$ has a narrow maximum, the shape of the spectrum is of Lorentz type,

$$G(\omega) = \frac{\tau^{-1}}{\tau^{-1}+\omega^2}. \tag{8}$$

4. AE in metals

The starting point for applications of AE that appear in metals was investigation of the cracking processes occurring in macro-scale, when metal is regarded as a homogeneous body. It appeared before long, however, that in order to understand the essence of these processes it is necessary to investigate the relationship between the changes of metal microstructure and the signals generated by the changes [17].

The main source of AE in metals are motions of dislocations. These motions take place as the result of external or internal stresses during fatigue processes, or local temperature variations. The necessary condition for AE to arise is the existence of courses of cumulation and release of the energy contained in a crystal lattice. It occurs as the results of changes of density and velocity of dislocation, what is described by the general relationship

$$n = f\left(N_m, \frac{\partial N_m}{\partial t}, \frac{\partial N_0}{\partial t}\right) \tag{9}$$

where: n — count rate, N_m — density of mobile dislocations, N_0 — the density of all dislocations.

It has been observed long ago that in certain metals an approximate, linear relationship exists between n and N_m, or n and $\frac{\partial N}{\partial t}$ [17].

The authors of [16] estimated that in the process of generation of a single AE impulse $10^5 \div 10^6$ segments of dislocation lines take part. The character of the dislocation motion depends on the ratio between the stress, and glide resistance. If the stress exceeds the glide resistance, dislocations move continuously, and in the opposite case, the step movement occurs. The dislocation is then slowed down by the potential barriers of the crystal lattice but, owing to the thermal activation, this obstacle may be overcome, and the dislocation can move to the next potential barrier. It is the so-called jerky glide.

A dislocation has a certain inertia, adequate to the deceleration time $\tau = 10^{-12} \div 10^{-10}$ s. During slowing down it then returns its energy to the neighbouring atoms, emitting an AE signal. The way of slowing down a dislocation in pure metals, at room temperature approaches $10^{-10} \div 10^{-9}$ m, therefore the entire effect occurs in micro-scale. Near the surface, the dislocation is exposed to an additional acceleration, and the complex processes of their interaction take place. The energy of the dislocations which reach the surface is partially utilized to create the surface roughness, the rest is the source of AE signals.

In a situation of external stresses, the originating macro- and micro-cracks alter the configuration of dislocations, and facilitate their passage to the surface.

A number of theories exist that connect the micro- processes which occur in metals with the generation of acoustic emission. The frequently applied model [19] assumes that the length of a free path of the dislocation, and its slide path must be longer than certain limiting values, for AE to occur. The length of the dislocation line which is capable of being displaced, is limited by distances to the pinned points, namely to the nodes of the crystal lattice. Taking this assumption, it may be stated that the minimal detectable deformations ε of the surface of the cylindrical sample of the section S are proportional to:

$$\frac{b L^3}{S d}, \tag{10}$$

where: L — diameter of the slide area, b — Burgers vector, d — spacing of the dislocation source.

Experimental investigations show that AE can not be detected for dislocation source spacing smaller than 0,4 μm. According to expectations, the influence of the grain diameter is observed. For example, in 99.99% aluminium AE counts rate maximum occurred for the grain diameter of 350 μm. Together with the increase of the diameter of grains, the slide path of dislocations also increases, therefore the AE rises. However, above a certain diameter of grains the possibility of the dislocation generation on the boundaries of grains decreases, and the activity of AE drops (Fig. 1).

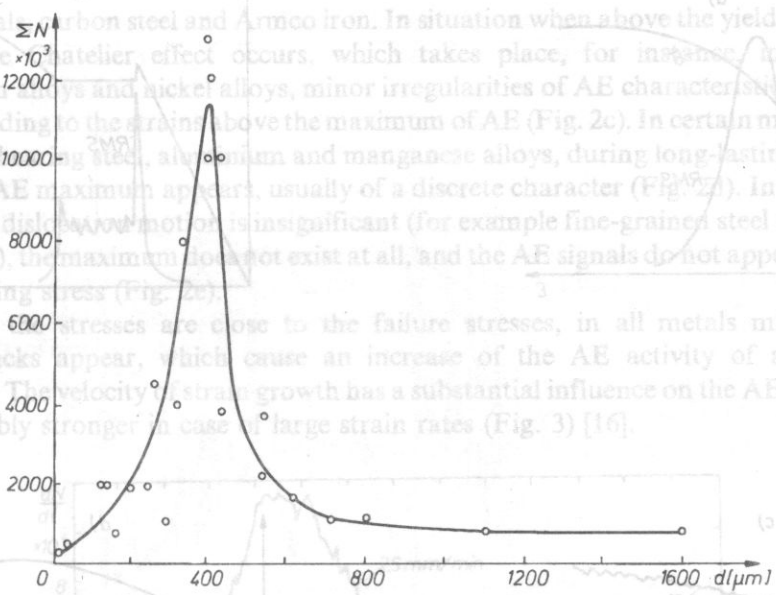


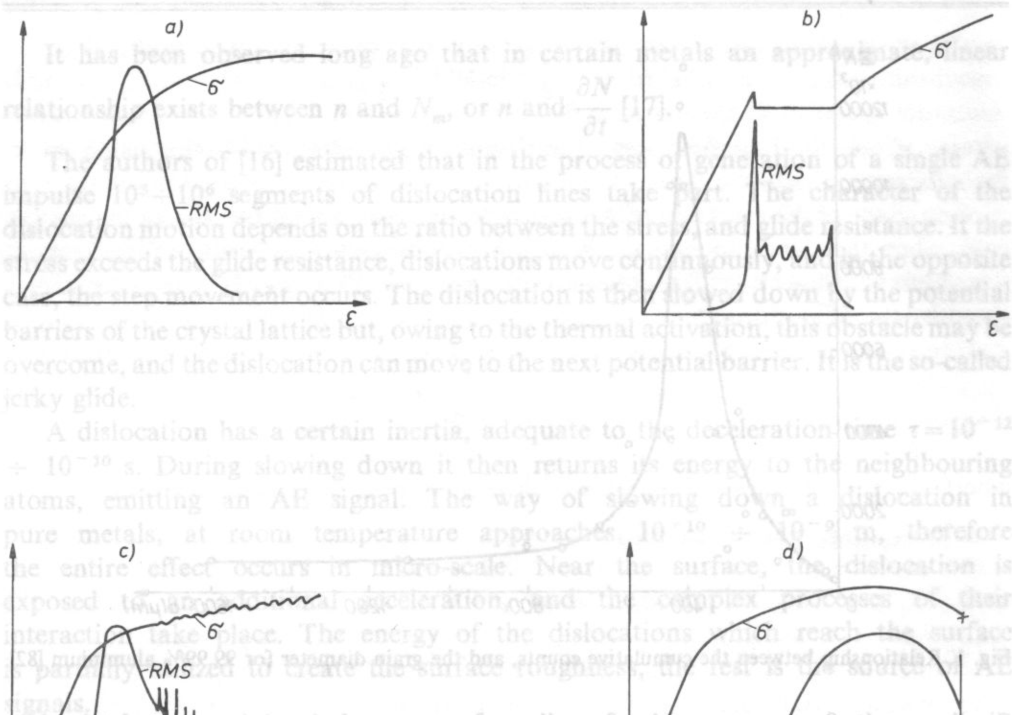
Fig. 1. Relationship between the cumulative counts, and the grain diameter for 99.99% aluminium [82].

Similar results for monocrystals of an alloy of copper and aluminium was obtained by PAWEŁEK [19]. The author presented a theory of AE generation during a step variation of stress. According to the theory, the main sources of AE are annihilations of dislocations during closure of the dislocation loops, produced by the Frank-Read sources.

The above considerations concern the material, the homogenous structure of which has not been disturbed by external loads. When the stress increases, and exceeds the yield point (plasticity limit) in metal, micro-, and then macro-cracks appear. The mechanism of their creation may be of different kinds. Open cracking occurs in metals of properties similar to ceramics, for instance in metals of body-centered cubic lattice (bcc). The reason of it are the concentrations of the edge dislocations. The effect is accompanied by typical discrete emission — fairly strong pulses, separated by periods of silence. Slide cracking occurs in metals of distinctly plastic properties, for example of face-centered lattice (fcc) structure (aluminium, copper). When the stress increases, the crack expands gradually, this being the result of the fact that at the crack tip a plastic zone appears, including great number of mobile dislocations. Acoustic emission is in this case of a mixed character, the discrete and continuous signals appear.

It appears that, according to the kind of metal the characteristics of the counts rate of AE as a function of stress will be of different form.

In the majority of metals the first maximum of AE occurs at the yield point, then the activity of AE drops (Fig. 2a). If the first signals appear before reaching this limit, and if in the stress-strain characteristics the Lueders plateau exists, then, after a single peak, the AE activity remains on a steady level within this plateau, after that it decreases and assumes a steady character (Fig. 2b). Such a characteristics have, among



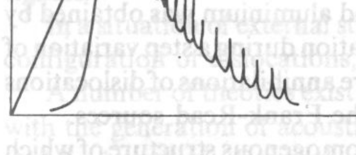


Fig. 2. RMS, AE, and stress versus strain for a) metals of typical characteristics of the stress-strain curve, b) metals showing the Lueders plateau, c) metals showing the Portvein – le Chatelier effect, d) metals showing the second AE maximum, e) metals showing weak mobility of dislocations [20].

other metals, carbon steel and Armco iron. In situation when above the yield point the Portvein-le Chatelier effect occurs, which takes place, for instance, in case of aluminium alloys and nickel alloys, minor irregularities of AE characteristics appear, corresponding to the strains above the maximum of AE (Fig. 2c). In certain metals, like titanium, bearing steel, aluminium and manganese alloys, during long-lasting strains, a second AE maximum appears, usually of a discrete character (Fig. 2d). In metals in which the dislocation motion is insignificant (for example fine-grained steel after heat treatment), the maximum does not exist at all, and the AE signals do not appear before the breaking stress (Fig. 2e).

When the stresses are close to the failure stresses, in all metals micro- and macro-cracks appear, which cause an increase of the AE activity of a discrete character. The velocity of strain growth has a substantial influence on the AE, which is considerably stronger in case of large strain rates (Fig. 3) [16].

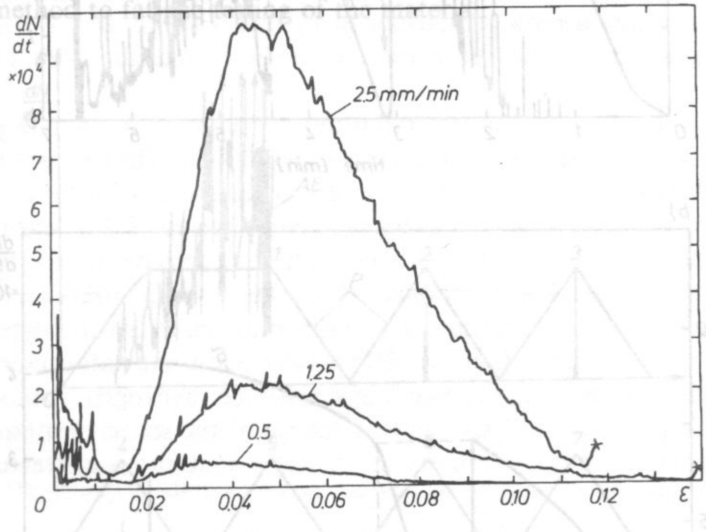


Fig. 3. Count rate during different velocities of the strain increase: (a) 0.5 mm/min, (b) 1.25 mm/min, (c) 2.5 mm/min [16].

For the application of the AE method it is important that AE signals should accompany these changes of material microstructure which have not yet effected the load characteristics. The research of the degree of defectiveness of steel by the AE method was initiated in Poland by Z. PAWŁOWSKI [85]. The investigation of AE generated by microstructural changes has been developed by PILECKI and SIEDLACZEK [20], while PILECKI expanded the investigation of processes of motions of dislocations [21]. The same authors investigated in detail [22] the behaviour of railway rails. It has been demonstrated that the AE method is a valuable tool to monitor the fatigue. In a new material (Fig. 4a), the AE activity is much stronger than in the rails which have been used for a few years (Fig. 4b).

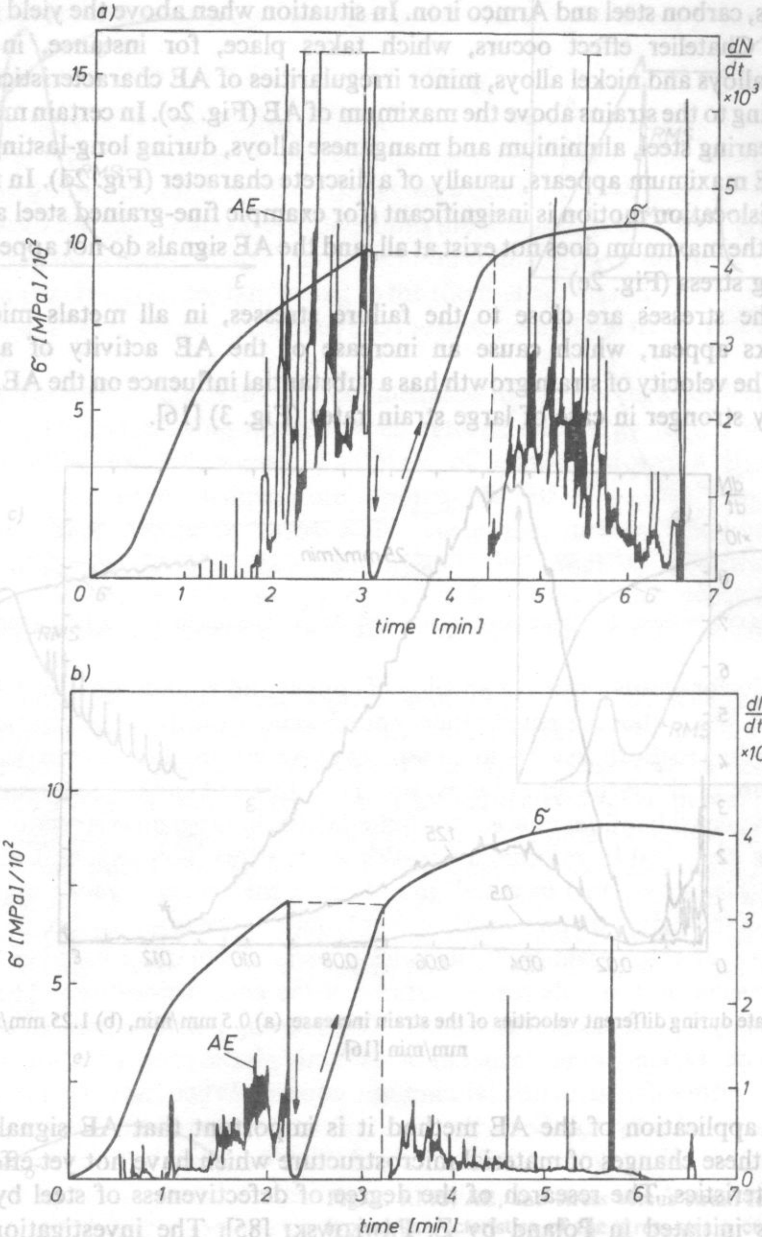


Fig. 4. Kaiser effect in steel St90PA (a) new, (b) exploited [20].

In metals an evident impact of the „history" of applied loads on AE exists. It is the Kaiser effect, based on shifting of the threshold of the AE initiation after relieving and repeated loading of the material (Fig. 4). Assume the material was exposed to the load σ_I, by which the AE activity appeared; after its relieving and the repeated loading, the

AE will appear only when $\sigma_{II} > \sigma_I$. This effect does not always appear, however. It is not observed in metals, in which AE appears also during unloading of the sample. It is relevant to the Bauschinger effect, which is based on the observation that after loading the material in one direction above the yield point, and subsequently in the opposite direction, the yield point of the material of the sample decreases. The occurrence of AE during application of cyclic loads to steel was the object of research of PILECKI and SIEDLACZEK [24], [22]. Three zones have been observed:

In the first zone, which comprises a few initial cycles, the Kaiser effect causes a gradual attenuation of AE signals, till their complete fading in the II zone, what is probably relevant to the fixed dislocation structure of the material. The III zone begins at the half of the number of cycles necessary to destroy the specimen; at this time gradually growing AE signals appear corresponding to the initiation of micro-cracks (Fig. 5). It should be noted that the AE method monitors the initiation of these cracks earlier than the optical methods, which opens considerable possibilities of application of the AE method to fatigue testing of the material.

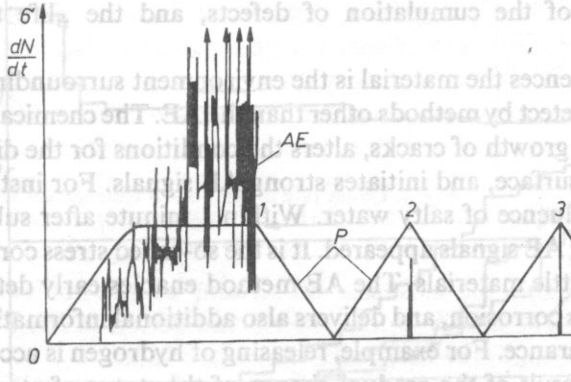


Fig. 5. AE at cyclic load [24].

The processes occurring during the cyclic loads are more complex than those at static loads. The state of dynamic equilibrium exists between production of the new dislocations during subsequent cycles, and the annihilation of the existing ones. The process of production of the new dislocations is proportional to the density of dislocations, while the process of annihilation is proportional to the square of that density, therefore this status of dynamic balance stabilizes only after a sufficiently large quantity of cycles [21]. It should be remembered, however, that the fatigue processes and the appearance of the AE signals, depend strongly on the state of the metal surface [23], and the motion of the dislocations emerging at the material surface increases of its roughness. The nucleation of the fatigue cracks begins therefore on the material surface, initiating the burst AE.

During the cyclic load of the order of 10 cycles per second, the counts rate values are distributed (as a function of time) apparently chaotically. However, as it has been indicated by PAWŁOWSKI [86], it is possible, by means of the cluster analysis, to determine certain regularities of the distribution and, on this basis, to estimate the progress of the cumulation of defects, and the „life time" of the specimen.

A factor which influences the material is the environment surrounding it, and this influence is difficult to detect by methods other than the AE. The chemically aggressive environment causes the growth of cracks, alters the conditions for the dislocations to emerge at the material surface, and initiates strong AE signals. For instance, PILECKI [87] investigated the influence of salty water. Within 1 minute after submerging the metal sample, the strong AE signals appeared. It is the so-called stress corrosion effect, which occurs also in brittle materials. The AE method enables early detection of the initial stages of the stress corrosion, and delivers also additional information about the mechanisms of its appearance. For example, releasing of hydrogen is accompanied by a burst AE, being the result of the gradual change of the status of atom activation, whereas the anode dissolution initiates the AE of a continuous character.

5. Superconductors and materials under high pressure

It seems that the AE method may become an unique tool for investigating the phenomena specific to the superconductive state. The objects of investigation by the AE method are, first of all, the superconductors of type II, because of their practical significance and wide application. These materials behave like ideal dielectrics only under the magnetic field $M<M_{CL}$, while under the field intensity $M_{CL}<M<M_{CZ}$ a so-called mixed state is observed. The external magnetics field generates then certain cores in the material, shielded by superconductive eddy currents. These are fluxes which form a spatial lattice, pinned on the defects of material microstructure. The fixed fluxes enable a resistanceless current flow. At the instant when the Lorentz forces become greater than the pinning forces, the flux lattice is set in motion, the residual stresses are relaxed, and the AE signals are generated, a significant role being played at it by the effects of magnetic hysteresis [26].

Results of the Polish research by WOŹNY and others [27], [28], [82] have indicated that the count rate of AE in an electromagnet NbTi, measured in liquid helium of temperature 4.2 K, in the cycle of increasing and subsequent decreasing of the current ($I > I_c$), attains its maximum near the critical current. In the two next cycles the count rate decreases considerably (Fig. 6). These investigations confirm the dependance of AE activity on the effect of flux pinning. The reduction of the count sum in the successive measuring cycles is caused possibly by "freezing" of the flux lattice. A formal analogy to the Kaiser effect exists here. The same authors investigated a superconductive high temperature ceramics $YBa_2Cu_3)O_x$, during variations of the temperature.

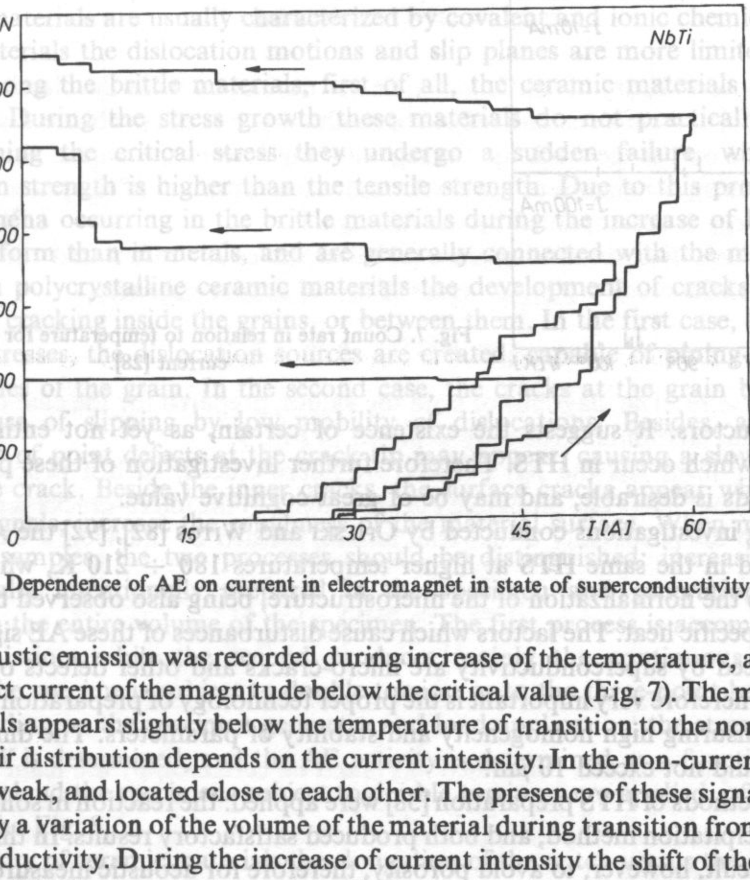


Fig. 6. Dependence of AE on current in electromagnet in state of superconductivity [28].

The acoustic emission was recorded during increase of the temperature, and for the flow of direct current of the magnitude below the critical value (Fig. 7). The main group of AE signals appears slightly below the temperature of transition to the normal state, whereas their distribution depends on the current intensity. In the non-current state the signals are weak, and located close to each other. The presence of these signals may be explained by a variation of the volume of the material during transition from the state of superconductivity. During the increase of current intensity the shift of the group of pulses toward higher temperature takes place, the signals are broadened and appear also at the end of the transition to the normal state. It is relevant to the increase of participation of the intercrystalline bonds in the current passage.

An essential statement of the quoted authors is that during the cyclic changes of current, without leaving the superconductivity state, the AE activity in high-temperature superconductors is several times lower than in the classical

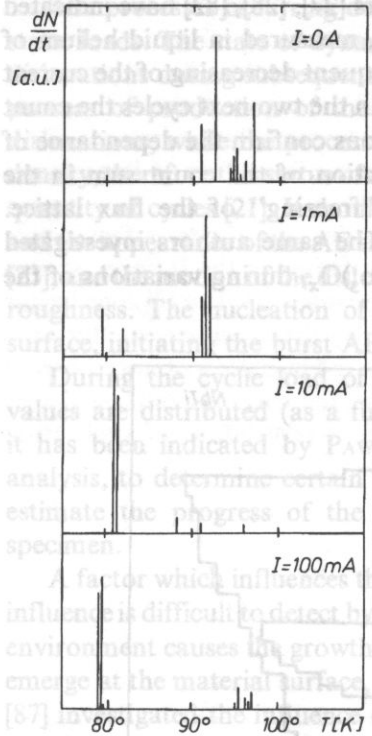


Fig. 7. Count rate in relation to temperature for four values of current [28].

superconductors. It suggests the existence of certain, as yet not entirely known processes which occur in HTS. Therefore further investigation of these processes by AE methods is desirable, and may be of great cognitive value.

During investigations conducted by Opilski and Witos [82], [92] the AE maxima were found in the same HTS at higher temperatures 180 ÷ 210 K, which may be relevant to the normalization of the microstructure, being also observed by measurements of specific heat. The factors which cause disturbances of these AE signals which are produced by superconductivity are micro-cracks and other defects of the tested samples. Therefore very important is the proper technology of preparation of the HTS samples, ensuring high homogeneity and stability of parameters. The dimensions of grains should not exceed 10 μm.

Two methods of HTS preparation [58] were applied: the reaction in solid state, and the co-precipitation method, and both produced satisfactory results. In thick samples it was difficult, however, to avoid porosity, therefore for acoustic measurements thin layers of HTS were applied. The $YBa_2Cu_3O_{7-x}$ was spread on the $NbLiO_3$ substrate. The attenuation of ultrasonic wave was investigated by means of the edge transducers. A distinct increase of attenuation at the region of critical temperature was observed. Also strong deformation of the sequence of echoes has been noticed, which is probably relevant to local mechanical stresses or structural changes of the medium. In the critical point minor variations of the velocity followed, of the order of $\Delta c/c = 10^{-3}$.

As it results from these observations, the distinct interdependence exists between the AE activity and the changes of acoustic properties of the medium for HTS. It seems that a qualitative research of this interdependence might contribute to a better understanding of the phenomena which occur in the region of the critical temperature.

In addition to superconductivity, the case which has been investigated by the AE methods is exposition of the material to high pressure. Heterogeneous materials, such as metal powders, and multiphase materials are of concern in the case. The research in this area has been initiated by WITCZAK [29].

6. AE in brittle materials

Brittle materials are usually characterized by covalent and ionic chemical bonds. In such materials the dislocation motions and slip planes are more limited than in metals. Among the brittle materials, first of all, the ceramic materials should be mentioned. During the stress growth these materials do not practically deform. After reaching the critical stress they undergo a sudden failure, whereas the compression strength is higher than the tensile strength. Due to this property, the AE phenomena occurring in the brittle materials during the increase of load, have a different form than in metals, and are generally connected with the micro-crack creation. In polycrystalline ceramic materials the development of cracks occurs in the form of cracking inside the grains, or between them. In the first case, because of the shear stresses, the dislocation sources are created, capable of pining-up on the opposite sides of the grain. In the second case, the cracks at the grain boundaries open because of slipping by low mobility of dislocations. Besides, a diffusion mechanisms of point defects at the crack tip may appear, causing a slow development of the crack. Beside the inner cracks, the surface cracks appear which, apart from AE signals, increase the roughness of the material surface. When monitoring the AE in samples, the two processes should be distinguished: increasing of the notch, usually intentionally prepared in the specimen and generation of micro-cracks in the entire volume of the specimen. The first process is accompanied by a burst emission, while the second produces mainly the continuous emission. Generally the specimens subject to double torsion or to the three-point bending are used; depending on the specimen geometry and load application, the stress intensity coefficient K is determined, and the AE activity is determined as a function of this factor. In Poland the specimens subject to double torsion were applied, of the shape shown on the Fig. 8.

In majority of ceramic materials the elongation of the notch versus the coefficient K has four ranges. During the loading below K_0 the standard notch does not change. In the range II, $K_0 < K < K_I$, the velocity of the notch expansion depends on the increase of K; in the range III, when $K_I < K < K_{II}$ in spite of growing load, the velocity of the notch elongation remains constant, in the range IV, when $K_{II} < K < K_c$, the notch increases quickly enough, and after reaching the critical value it grows violently till the failure of the sample.

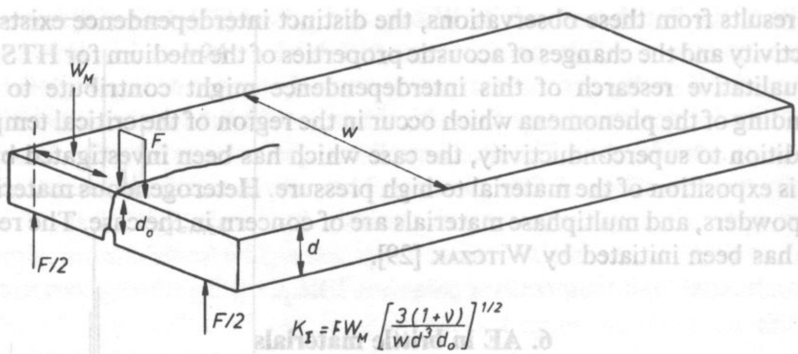


Fig. 8. Sample for double torsion [32].

The fracture theory of brittle materials has developed from the classical works of GRIFFITH [30] to form an extensive field of mechanics. For the problems discussed here it is essential that at the crack tip, the region of high stress and partial plastic yielding appear, causing the growth of the crack, and transformation of the potential into the kinetic energy is accompanied by the AE signals.

It has been discovered long since [31] that the count rate n and the velocity of extension of the crack υ plotted versus K are of similar character

$$n = BK^{m'}, \quad \upsilon = AK^{m}, \tag{11}$$

whereas $m \approx m'$. The diagrams of both the values, prepared for the case of porcelain ceramics and aluminium oxide are depicted in Fig. 9.

Another form has the AE initiated by micro-cracks, such a process being of a statistical character. The probability of occurrence of the micro-cracks producing AE is equals to the probability of material failure, defined by the Weibul's distribution

$$\Pi = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_r}\right)\right]^r. \tag{12}$$

where: σ_r and r are characteristic constants of the distribution for the material in question.

The complex research performed in Poland on ceramics, by the team directed by RANACHOWSKI [32], [81], [82], [83], enabled us to collect the experimental data concerning the AE activity as a function of load, and the relationship between AE and the material strength.

Testing of the sample consists of the three stages: (1) linearly increasing load, $\dot{\sigma}$ = const, (2) constant load, σ = const, and (3) — unloading, $\dot{\sigma}$ = const. The analytical formulae have been derived for count rate at each stage. The combined effect of the micro-crack creation, and elongation of the cracks for constant loads σ_2 and $\sigma_1 = 2\sigma_2$ is shown in Fig. 10. As it can be seen, after a certain period of time the sudden increase of AE starts, preceding the failure of the sample.

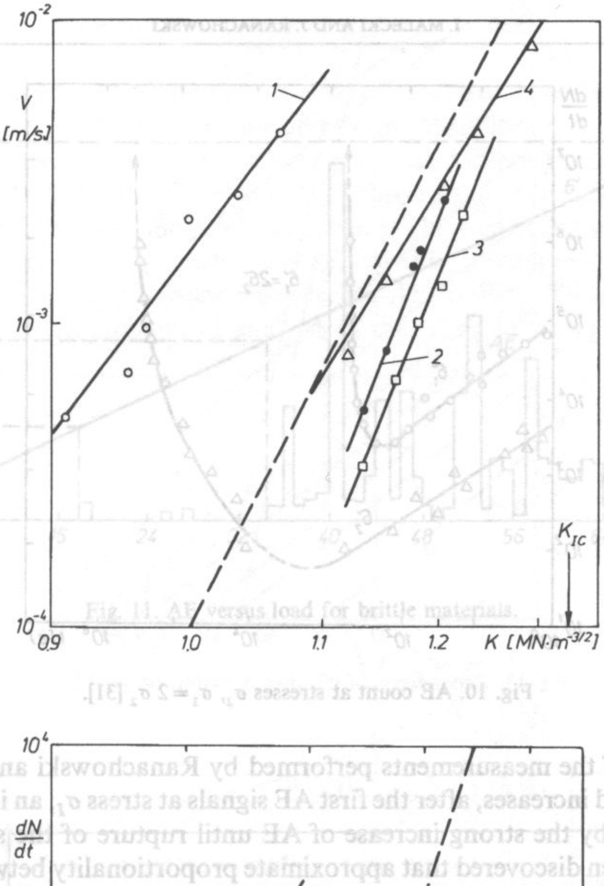


Fig. 9. AE count rate and velocity of notch elongation [83].

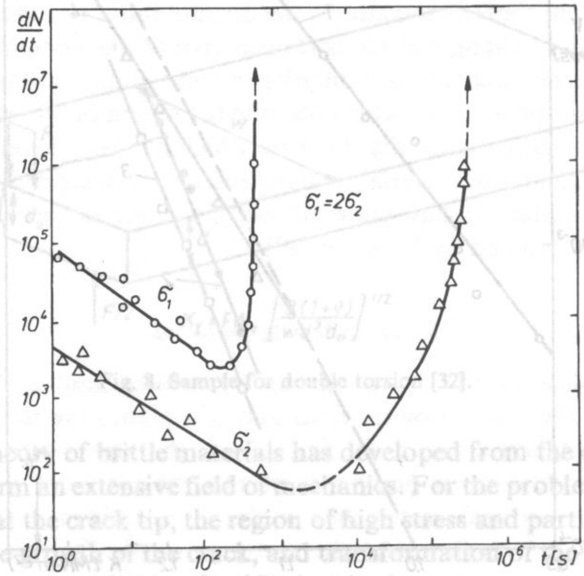


Fig. 10. AE count at stresses σ_2, $\sigma_1 = 2\,\sigma_2$ [31].

The results of the measurements performed by Ranachowski and his team show that when the load increases, after the first AE signals at stress σ_I, an interval of silence comes, followed by the strong increase of AE until rupture of the sample (Fig. 11). Besides, it has been discovered that approximate proportionality between σ_I or F_I and the failure stress exists, which is illustrated in Fig. 12. This relationship may be regarded as a basis for determination of the strength of ceramics by the AE method. The above-mentioned team investigated also the possibility of assessment of the "life-time" of ceramics by the AE method. The "life-time" is determined at the overload R in relation to the operating stress. On the grounds of the measurement of the AE counts rate, which accompany elongation of the crack during overloading, it is possible to determine the minimal time t_{min}, necessary to break the sample. This time is a function of the stress intensity factor K, and the material constants. Figure 13 presents (in logarithmic scale) the dependance of t_{min} on different values of the overload. The straight lines which cross the graph coincide with the probability of material failure.

The AE method appeared to be very useful in detection of micro-cracks produced in ceramic materials as an effect of thermo-mechanical stresses. The work on it has been developed by the team of Ranachowski. Figure 14 presents the mechanical strength and AE versus thermal shock difference for alundum material. As it can be seen, AE appears considerably below the critical temperature, afterwards it maintains a steady level, and rapidly grows at the temperature of the shock ΔT 800°C. The analysis of the AE parameters may then be useful in investigating the various phases of the thermal cracking process, whereas it appears that the descriptors which yield especially valuable information are: duration of the event, and its amplitude. The low

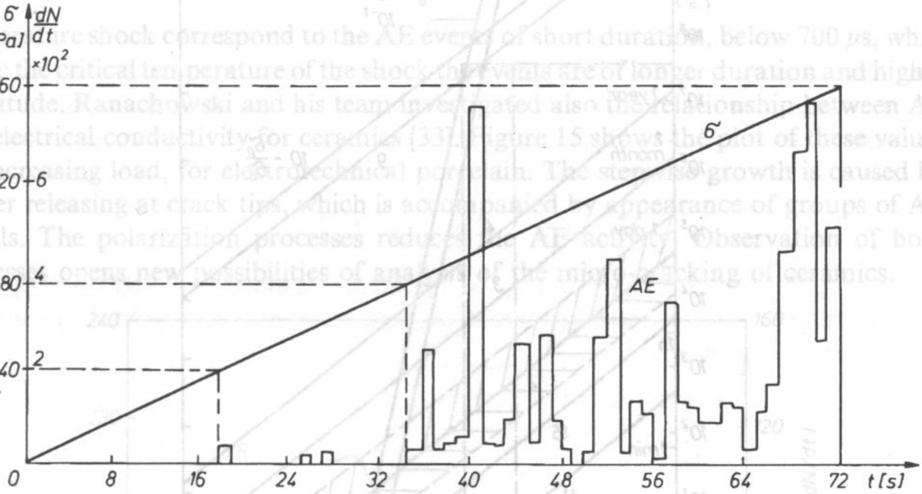


Fig. 11. AE versus load for brittle materials.

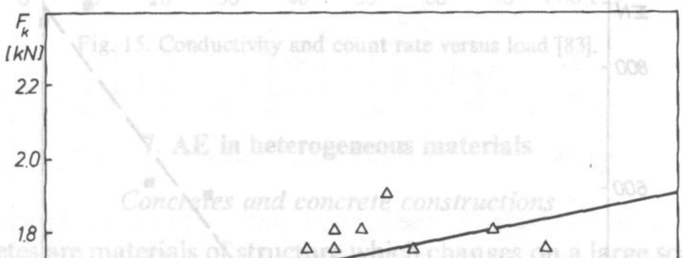


Fig. 12. Dependence of mechanical strength F_K on loading force F_0 of appearance of first AE signals for alumina ceramics [83].

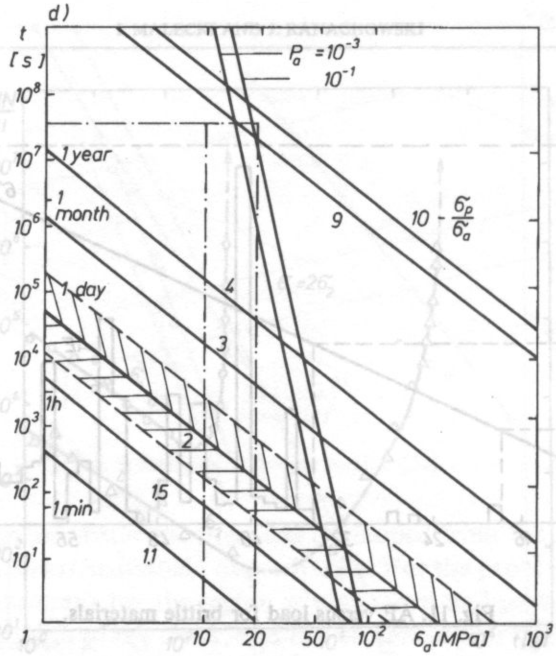


Fig. 13. Dependence of life time duration on load [83].

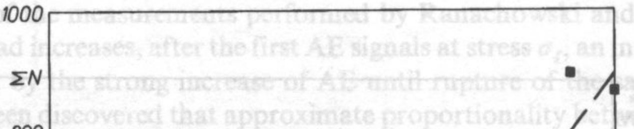


Fig. 14. Strength and AE activity versus temperature difference of thermal shock [83].

temperature shock correspond to the AE events of short duration, below 700 μs, while above the critical temperature of the shock the events are of longer duration and higher amplitude. Ranachowski and his team investigated also the relationship between AE and electrical conductivity for ceramics [33]. Figure 15 shows the plot of these values for increasing load, for electrotechnical porcelain. The stepwise growth is caused by carrier releasing at crack tips, which is accompanied by appearance of groups of AE signals. The polarization processes reduces the AE activity. Observation of both processes opens new possibilities of analysis of the micro-cracking of ceramics.

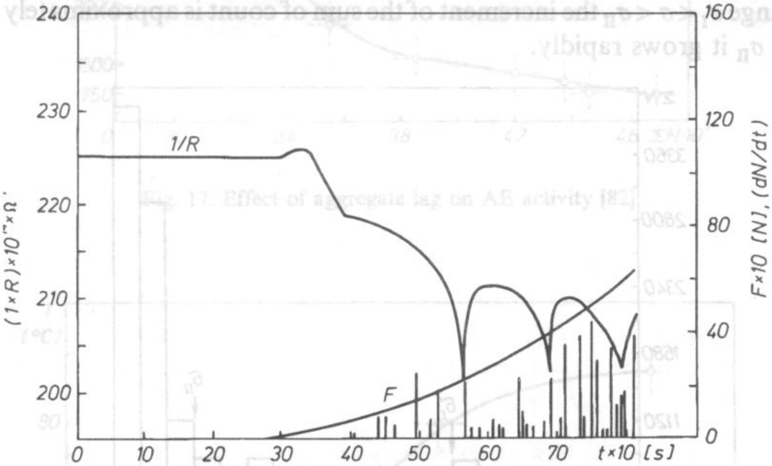


Fig. 15. Conductivity and count rate versus load [83].

7. AE in heterogeneous materials

Concretes and concrete constructions

The concretes are materials of structure which changes on a large scale, subject to various proportions of components, and the applied technologies; nevertheless, they hold certain common features, the behaviour under load and presence of long-term structural variations being most important [34]. The processes which occur under the load may be divided into three phases. In the first phase of stable initiation, the micro-cracks existing already in the state of production do not increase, whereas the new, also stable micro-cracks appear. In the second phase the propagation of the existing micro-cracks follows, as a result of the destruction of adherence between the grains of the aggregate and the mortar. In the third phase unstable development of the micro-cracks begins, ending with failure of the material. Stresses σ_I and σ_{II}, which are accordingly named the initiating stress and critical stress, are characteristic for the transitions from one phase to another. The identification of both the stresses is of primary importance for the evaluation of the operating parameters of concrete, and for the elaboration of the optimal technology of manufacturing.

The fact that both the stresses are accompanied by the characteristic AE signals, constitutes a basis for a practical application of the AE method to the evaluation of the quality of concrete (HOŁA–MOCZKO [35] with Z. RANACHOWSKI [77]). It appeared that the best characteristics of the effects yields the gain ΔN of the sum of count ΣN, between the two stress levels of n and $n+1$

$$\Delta N = \Sigma N_{n+1} - \Sigma N_n$$

The plot of $\Delta N(\sigma)$ is shown in Fig. 16. ΔN increases almost linearly up to the load σ_{I}, in the range $\sigma_{\mathrm{I}} < \sigma < \sigma_{\mathrm{II}}$ the increment of the sum of count is approximately constant, and above σ_{II} it grows rapidly.

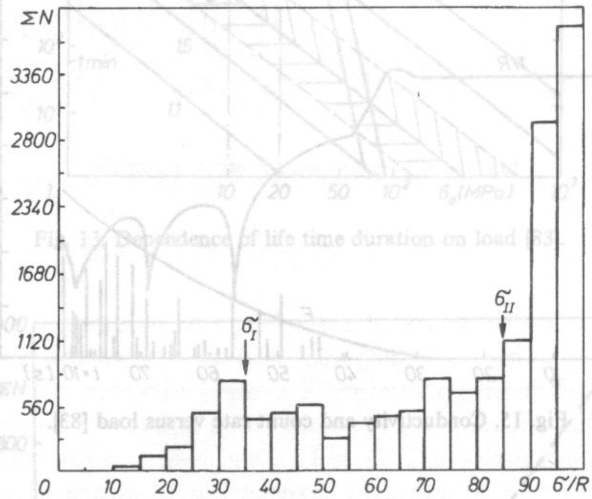


Fig. 16. Dependence of count rate on stress increase [77].

As it has been demonstrated by the investigations of PYSZNIAK, MOCZKO, HOŁA [35], [36], graining of the aggregate has a considerable influence on the sum of count, for instance the apparent thickness of the lagging of the aggregate by the mortar (Fig. 17). When the aggregate is finer, and the lagging thicker, the material becomes more homogeneous, having less micro-cracks, which are the sources of AE. The same author investigated [37] the effect of moisture on the strength of concrete, and found that the counts difference depends on the moisture contents. Presently an artificial curing of concrete is applied on a large scale. As it has been found [38], thermal treatment causes the increase of the sum of count when the concrete is loaded up to failure (Fig. 18). It is probably due to the increased number of micro-cracks, because the products of concrete hydration, which appear at elevated temperature, have more coarse structure. ΣN depends on the temperature of heat treatment and on its duration.

As one can see, the AE method yields comprehensive information about parameters of the complex processes which occur during production and operation of concretes.

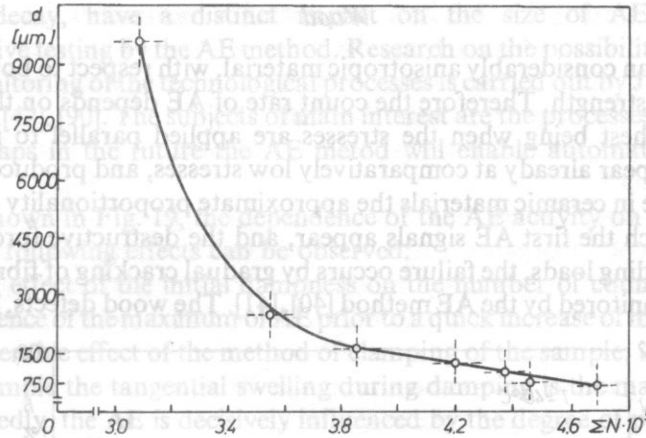


Fig. 17. Effect of aggregate lag on AE activity [82].

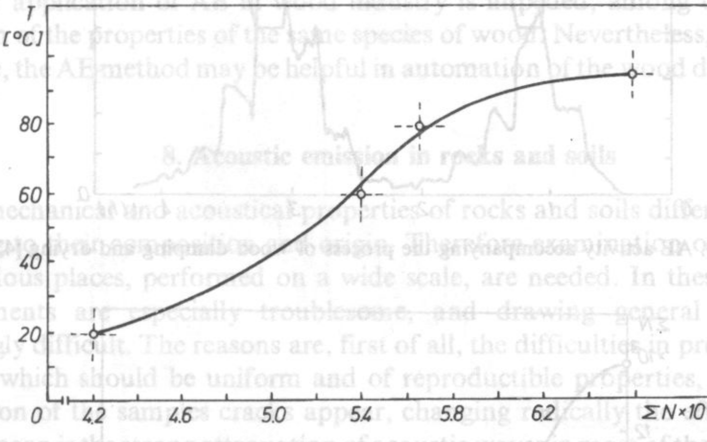


Fig. 18. Effect of thermal treatment of concrete on sum of count [82].

Hoła and his team have also undertaken a work on comparing the efficiency of the AE method, and the method of measurements of the velocity variations of the ultrasonic wave; however, they have not obtained explicit results. The correlation of results of both methods is a more general problem, it involves also other materials. The difficulty in interpretation of the results is caused, among other factors, by great scatter of the experimental data, and also by a quite different form of the plots of ultrasonic pulse and AE counts rate versus the stress. Some authors claim the AE method monitors micro-cracks later than the ultrasonic pulse velocity method does, however no consensus on the subject has been reached among specialists as yet [39]. In any case, further comparative studies seem to be very desirable.

Wood

The wood is an considerably anisotropic material, with respect to both its structure and mechanical strength. Therefore the count rate of AE depends on the direction of stresses, the highest being when the stresses are applied parallel to its fibres. The micro-cracks appear already at comparatively low stresses, and produce first acoustic signals. Likewise in ceramic materials the approximate proportionality exists between the force at which the first AE signals appear, and the destructive force. During the long-lasting bending loads, the failure occurs by gradual cracking of fibres, which may be effectively monitored by the AE method [40], [41]. The wood defects, as for instance

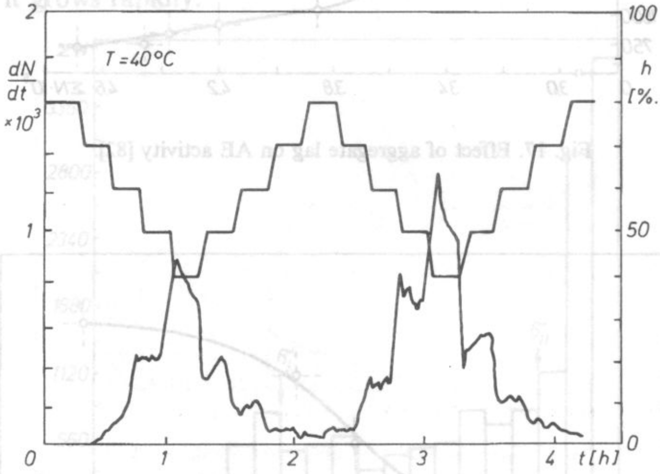


Fig. 19. AE activity accompanying the process of wood damping and drying [42].

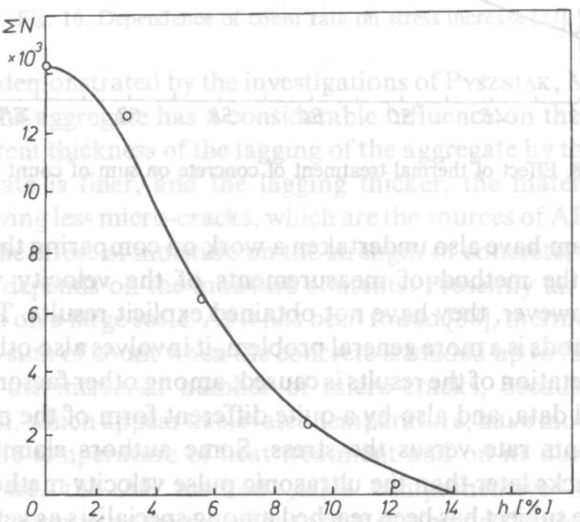


Fig. 20. Effect of initial wood dampness on count rate [82].

knots and decay, have a distinct impact on the size of AE, which enables non-destructive testing by the AE method. Research on the possibilities of application of AE to monitoring of the technological processes is carried out by J. Raczkowski and W. Moliński [42], [90]. The subjects of main interest are the processes of damping, and drying. Perhaps in the future the AE metod will enable automatic control of the processes.

As it is shown in Fig. 19, the dependence of the AE activity on dampness is very distinct. The following effects can be observed:

— strong effect of the initial dampness on the number of counts (Fig. 20),

— occurrence of the maximum of AE prior to a quick increase of material shrinkage,

— considerable effect of the method of clamping of the sample; in case of a simply supported sample the tangential swelling during damping is the main source of AE. Undoubtedly, the AE is decisively influenced by the degree of plasticity of wood, which increases together with the increase of its dampness.

The same authors investigated also the impact of the mechanical treatment on the character of AE. They have found, for example, that the inclination angle of the cutting tool, and its orientation with respect to the fibres, considerably alters the AE count rate.

Wider application of AE in wood industry is impeded, among other things, by dispersion of the properties of the same species of wood. Nevertheless, it seems that in the future, the AE method may be helpful in automation of the wood drying processes.

8. Acoustic emission in rocks and soils

The mechanical and acoustical properties of rocks and soils differ fundamentally according to their composition and origin. Therefore examination of samples taken from various places, performed on a wide scale, are needed. In these cases the AE measurements are especially troublesome, and drawing general conclusions is accordingly difficult. The reasons are, first of all, the difficulties in preparation of the samples, which should be uniform and of reproductible properties, because during preparation of the samples cracks appear, changing radically the effect of AE. The second reason is the strong attenuation of acoustic waves in most of the materials being tested, which decreases the intensity of the signals received.

In spite of these obstacles, the investigation of acoustic effects occurring in rocks has been drawing the attention of engineers and scientists for a long time [43]. It was expected that the observation of the AE signals would enable an early warning of a mining catastrophe (a crump) [44], or a catastrophic failure of a technical object, like a water dam. The results were only partially successful, and limited they were to the strictly determined local conditions. Nevertheless, further attempts in this direction seem to be promising, a thorough recognition of the AE characteristics of rock materials being necessary, what requires an extensive laboratory research. Such research is carried out in Poland by three centres, and concernes the coal and accompanying beds in Upper Silesia, the copper ore beds in the Legnica basin, and the soils typical for foundations of engineering structures.

Opilski and Witos [45], [80] have conducted a comprehensive study on the geological beds of Upper Silesia from the point of view of application of the AE method, and they came to certain general conclusions. During loading of the rock four phases of AE activity may be distinguished [46], [47].

(1) closing of the initial micro-cracks, usually accompanied by a continuous AE, of constant counts rate,

(2) the elastic strain, when the count rate begins to grow,

(3) the process of stable propagation of micro-cracks, during which the counts rate increases, subsequently followed by its reduction within a certain range of loads,

(4) the unstable propagation of cracks, leading to failure, accompanied by a rapid rise of AE.

A typical diagram of count rate for dull coal is shown in Fig. 21, however considerable differences in the characteristics may be observed, depending on the material. Together with the progress of the destruction process, the changes of the

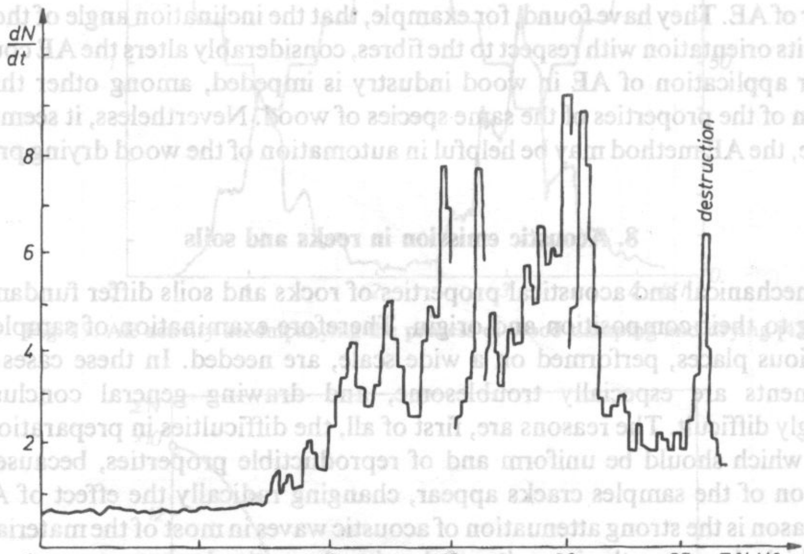


Fig. 21. Dependence of count rate on load for dull coal [81].

frequency distribution may be observed, namely the occurrence — in addition to the 60 ÷ 80 kHz frequency band of the second maximum in the band of 80 ÷ 160 kHz. The quoted authors concluded that the crucial factor was the capability of accumulation of the elastic energy by the rock materials, and introduced the division of materials into the three groups:

(1) the materials that practically do not accumulate the energy, e.g. bright coal,

(2) the materials that accumulate the energy partially, e.g. dull coal,

(3) the materials that strongly accumulate the energy, e.g. sandstone.

A diagrammatic characteristics of the AE activity for the three types of materials is shown in Fig. 22. The Kaiser effect at a variable load is observed, however, depending on the materials damage, it is subject to considerable deviations.

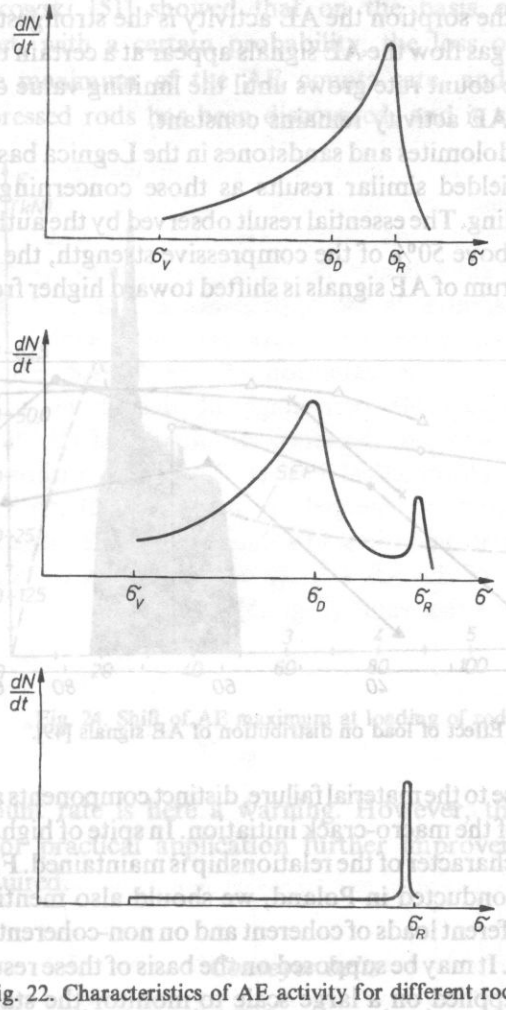


Fig. 22. Characteristics of AE activity for different rock types [82].

It is important for practical applications that, in the majority of cases, the intensified AE activity appears still in the phase of stable micro-cracks, thus warning against the approaching failure of the material. The observations that have been performed hitherto *in situ* do not entitle us to draw any quantitative conclusions as to the relationship between the growing AE activity and a approaching mining catastrophe; nevertheless there are some reasons to expect that such a relationship exists, and its evaluation will be the subject of further research.

The reasons of mining catastrophes might also be the gas explosions. Therefore the investigations initiated in Poland by the team directed by Z. Pawłowski [84] on the AE signals which accompany the sorption, desorption, and the flow of gas (CO_2) in coal samples, might be of a practical significance. Though the results depend strongly on the kind of material and the way of the sample preparation, nevertheless certain rules have been discovered. During the sorption the AE activity is the strongest at the beginning of the process. During the gas flow the AE signals appear at a certain threshold value of the overpressure, then the count rate grows until the limiting value of overpressure is reached, after which the AE activity remains constant.

The investigations on dolomites and sandstones in the Legnica basin, carried out by Jaroszewska [48], [49], yielded similar results as those concerning the general AE characteristics during loading. The essential result observed by the author is the fact that while the load increases above 50% of the compressive strength, the maximum of the energy density in the spectrum of AE signals is shifted toward higher frequencies. On the

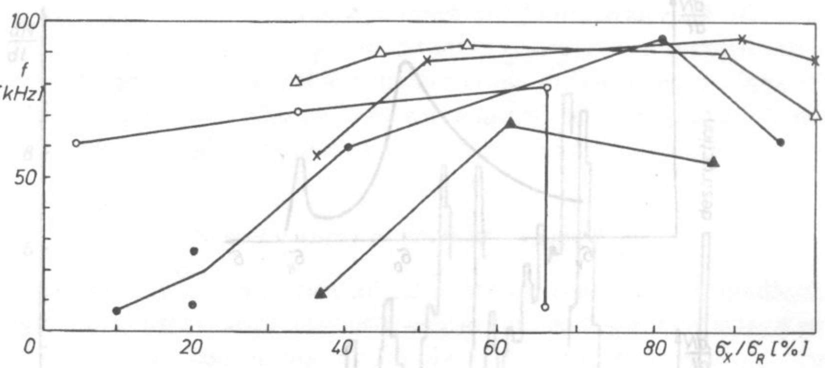


Fig. 23. Effect of load on distribution of AE signals [49].

other hand, at the loads close to the material failure, distinct components at low frequencies appear, what is the result of the macro-crack initiation. In spite of high dispersion of the data (Fig. 23), the general character of the relationship is maintained. From amongst the research that have been conducted in Poland, we should also mention the paper by Skrynicki [50] on AE at different loads of coherent and on non-coherent soils, at different temperature and humidity. It may be supposed on the basis of these results that in future the AE methods will be applied on a large scale to monitor the stability of soils.

9. AE in machinery elements and technological processes

Unlike the samples of materials, which are submitted to standard, laboratory tests, the components of machines and engineering constructions are the objects in which complex states of stresses exist, and the AE signals depend not only on materials and sample parameters, but also on the shape of the object. As an example, certain investigations carried out in Poland will be discussed.

Rods

Typical construction components are rods. The classical measuring methods not always enable an accurate determination of the instant of its stability loss. It is especially important in statically indeterminate structures. The investigations of Kowal and Senkowski [51] showed that on the basis of AE observation it is possible to predict, with a certain probability, the loss of stability. Namely, the shift between the maximum of the AE counts rate, and the limit load bearing capacity of compressed rods has been discovered, and is shown in Fig. 24. A fast

Fig. 24. Shift of AE maximum at loading of rod [51].

growth of the count rate is here a warning. However, these data are qualitative ones, therefore for practical application further improvements of the measuring technique are required.

Conveyer belts

An example of application of AE for the selection of machine components is a method of testing of horizontal conveyor belts in mining industry, developed by A. Opilski with his team [52]. The authors found that measurements of events rate and sum of count enable arranging the samples of belts according to their tensile strength. The main difficulty is that the results of measurements vary considerably, according to the dimensions of the sample; it is not possible, therefore, to establish explicitly the standard AE activity, leading to rejection of the belt.

Composites

A separate problem are the AE effects in composite materials and structures. The process of cracking occurring in composites under load depends on the structure of the composite, however the five following phases of the process may usually be distinguished: cracking at the fiber-matrix interface, cracking across the layers of laminate, delamination, fibre decoupling, cracking of fibres. The AE method enables monitoring and separation of the phases, what would be difficult on the basis of the classical methods of material testing. The AE method is also applied to the control of long-term changes, characteristic for structures of composite materials. For the purpose, a very complicated measuring instrumentation is used. In Poland the studies on composites, especially on the glass fiber-reinforced pipes, are carried out by Gołaski and Radziszewski [53]. They found a distinct relationship between the AE signals and the phases of cracking of these pipes; especially essential is the appearance of the first AE signals at the beginning of the process, when the cracks are undetectable by classical methods.They investigated also the extension of the Kaiser effect appearaing in composites [54]. A considerable percentage of defects in composite pipes is produced by the stress corrosion, therefore monitoring of the degree of the stress corrosion is of considerable practical impact. The same authors studied [54] the behaviour of loaded pipes, submerged in neutral media (oil), as well as in chemically active ones (hydrochloric acid solution), and they discovered that in the latter case a distinct rise of the AE activity occurs after a certain period of time. This time depends on the stress value (Fig. 25).

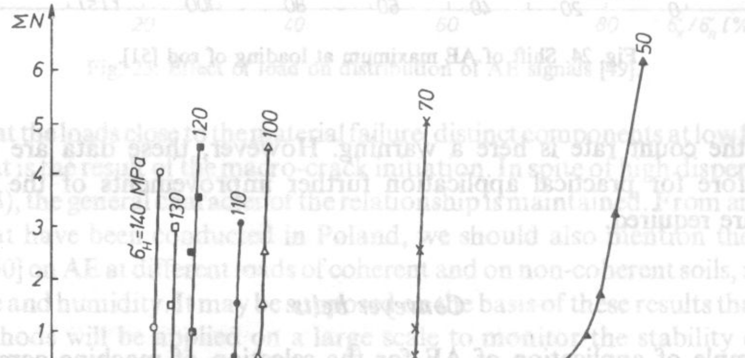


Fig. 25. Effect of environment on stress corrosion of composite pipes [54].

Earlier, Z. Pawłowski [85] investigated the dependence of the AE counts sum on the load and the time of its action on the glass fibre-reinforced polyester, coming to an empirical formula.

Welding

One of the oldest applications of the AE method was the control of welding [13]. Considerable troubles have been encountered, however, mainly in regard to separation of these AE signals which are generated by welding defects, from the background noise accompanying the welding process. The development of the measuring technique made it possible to overcome these difficulties, mainly by extraction of the characteristic features of the AE signals generated during welding, which appear within a certain period of time after passing of the electrode. In practical application of the method it is possible to detect [55], with a considerable reliability, welding cracks and slag inclusions. As an example, the dependence of the differences in AE signals on the quality of weld is shown in Fig. 26. The cracking processes still proceed, fading gradually, during a few hours after welding. Therefore in certain constructions, such as hulls of ships, the long-term AE monitoring is applied. An important example of using the AE methods in welding technology is a control of weld quality in high-pressure

Fig. 26. AE signals from (a) correct, and (b) incorrect weld [56].

pipelines for power plants. The adaptation of the method has been undertaken by Skubis and co-workers [56]. A number of samples with welds, cut out of pipelines, were investigated. A general increase of the AE activity was reported, even before plastic deformation, which conforms to the generally known observations in metals. Interesting results were reported concerning the acoustic emission during thermal treatment of a welded pipeline. A typical plot of the sum of count during the treatment is shown in Fig. 27. As it may be seen, the sudden increase of temperature of heated pipeline is accompanied by a rapid growth of the AE activity, which indicates potential possibilities of application of the AE method to monitoring the fitness-for-purpose o long-distance pipelines.

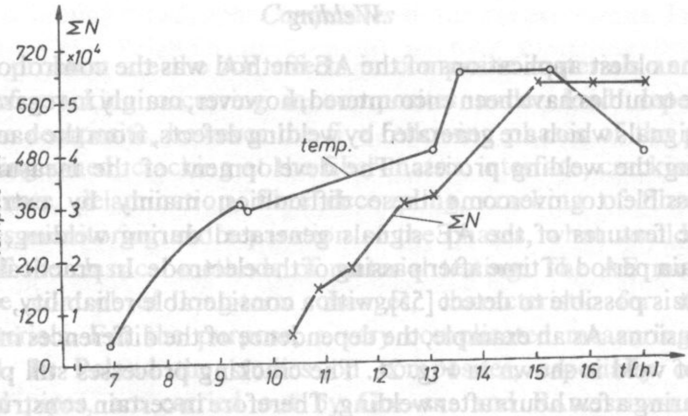


Fig. 27. Sum of count during thermal treatment of nozzle of pipeline [56].

Moving machine components

Just on the border line between the application of the AE method and the noise analysis methods are the studies on acoustic effects during operation of rolling bearings. These studies have been performed by the team directed by CEMPEL [57]. Possibilities of application of the AE method to the detection of faulty performance of moving parts of machines are the object of work of J. ADAMCZYK [91].

10. AE in physical, chemical and biological processes

Chemical processes

The studies which have been performed since the beginning of the eighties [59] demonstrated that AE is an effect which accompany many chemical reactions. The AE method can be therefore utilized, for instance just as the thermal analysis [60], to record the courses of these reactions. The AE measurements and the thermal methods can provide, however, additional information beyond the reach of non-thermal methods in this extent, for instance pertaining to phase transitions. Measurements of the AE which accompany chemical reactions are sometimes very troublesome, because of the low level of the AE signals, strong background noise from the measuring instrumentation, and lateral processes associated with the reaction. The studies performed by RZESZOTARSKA [62] in Poland were focused mainly on the oscillatory reactions. The two oscillatory reactions have been examined using the AE method: the reaction of Bielousov–Jabotynski type of oxidation of the malonic acid with bromates, catalyzed by ions of cerium, and the Bray–Liebhavski reaction of decompositon of hydrogen peroxide, in the presence of melanic acid and iodates. The acoustic

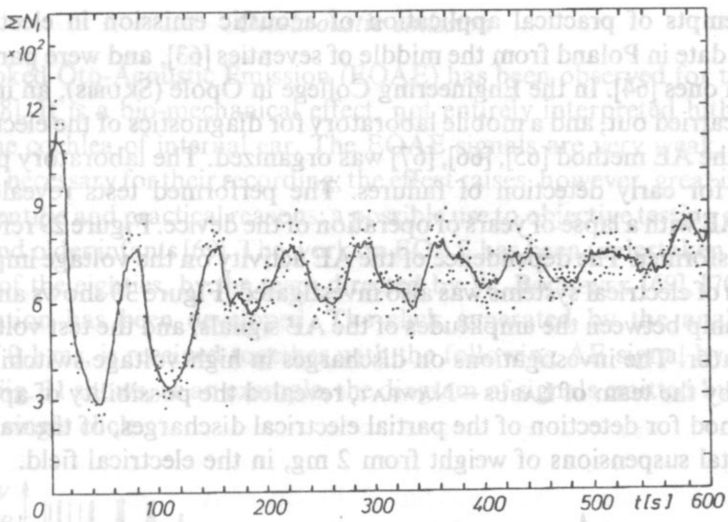


Fig. 28. Averaging AE events rate for B – L type reactions [62].

energy releases in the rhythm of the oscillatory liberation of the residual quantities of gas. As it turned out, the separate AE events assume various values, however, after averaging, a clear oscillatory time-dependence appears. Figure 28 shows a diagram, averaged for the B – J reaction, where the points mark the events rate measurements.

Presently the investigation of structural changes of complex compounds in solutions and in the solid phase takes place. The analysis of the power spectra of the separate AE signals, as well as their characteristics during the time of reaction, may deliver information about the physical – chemical sources of acoustic energy. It should be emphasized that these investigations require a measuring system of high-sensitivity (low noise level), and of a good time resolution, and then the application of statistical methods of the signal analysis.

Electrical discharges

The physical process which can be monitored by the AE method is the partial electrical discharge. These discharges initiate effects which can be audible, because they are confined within the band up to 2 kHz. However the detection of the AE signals of higher frequencies produced by very weak discharges is vital, since they inform about the initial stages of failure. Due to its unique feature, the AE method enables *in-service* monitoring of electrical power devices. However, because of a complex structure of the devices, it is difficult to assess quantitatively the electrical discharges on the ground of the parameters of the AE signals. The second limitation is due to the fact that the signals which are received are coming from discharges occuring in air and oil, whereas the signals approaching from inside of the insulation are strongly attenuated and usually not discernible.

The attempts of practical application of acoustic emission in electrical power engineering date in Poland from the middle of seventies [63], and were parallel in time with foreign ones [64]. In the Engineering College in Opole (Skubis), an investigation on AE was carried out, and a mobile laboratory for diagnostics of the electrical power systems by the AE method [65], [66], [67] was organized. The laboratory proved to be very useful for early detection of failures. The performed tests revealed a minor increase of AE with a lapse of years of operation of the device. Figure 29 refers to a high voltage transformer. The dependence of the AE activity on the voltage imposed to the components of electrical systems was also investigated. Figure 30 shows an example of the relationship between the amplitudes of the AE signals, and the test voltage applied to the insulator. The investigations on discharges in high voltage switching stations, carried out by the team of Łabus – Nawrat, revealed the possibility of application of the AE method for detection of the partial electrical discharges, of the value from 10 pC, and metal suspensions of weight from 2 mg, in the electrical field.

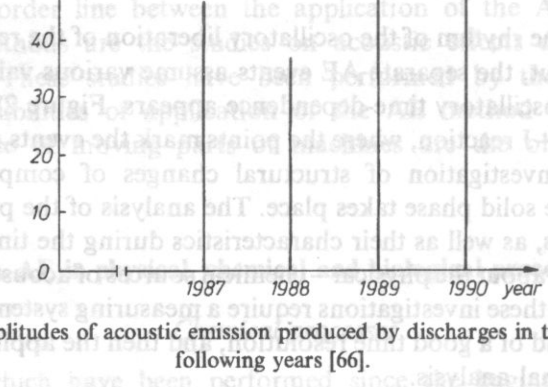


Fig. 29. Increase of amplitudes of acoustic emission produced by discharges in transformer, during four following years [66].

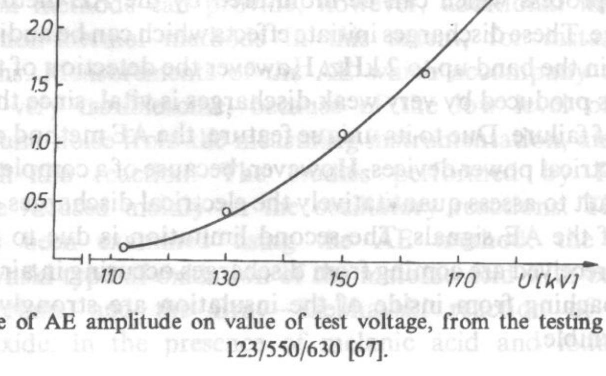


Fig. 30. Dependence of AE amplitude on value of test voltage, from the testing of insulator PKTNk 123/550/630 [67].

Oto-acoustic emission

The Evoked Oto-Acoustic Emission (EOAE) has been observed for the first time by Kemp [68]. It is a bio-mechanical effect, not entirely interpreted hitherto, which occurs in the cochlea of internal ear. The EOAE signals are very weak, so a special technique is necessary for their recording; the effect raises, however, great interest from both the scientific and practical reasons: a possible use to objective testing of hearing of new-born and older infants [69]. The work on EOAE has been undertaken in Poland in the middle of the eighties, by the team directed by W. Bochenek [69], [70]. A special instrumentation has been developed. The click generated by the analyzer of the duration of 0.1 ms, is received together with the following AE signal by a miniature earphone. Fig. 31 shows, as an example, the diagram of signals emitted by an ear after imposing a single click.

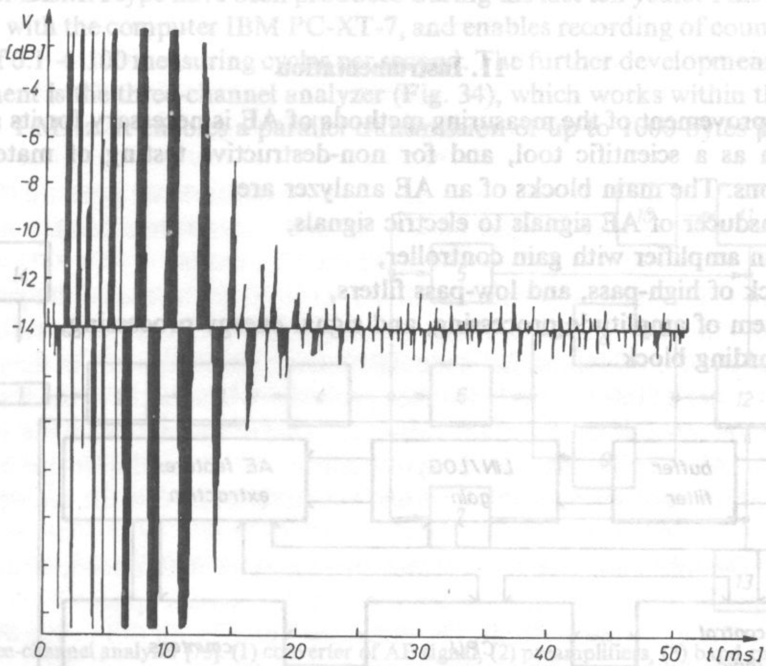


Fig. 31. Evoked oto-emission versus time as effect of single click [70].

The differentiation of the nonlinear component of AE has been performed (Fig. 32). The bars on the graph are proportional to the instantaneous values of these components. The existence of the nonlinear component seems to be an interesting information about the occurring processes. The results obtained are not unequivocal, they enable, however, to draw the conclusion that in the majority (approx. 80%) of young and healthy persons the EOAE clearly occurs.

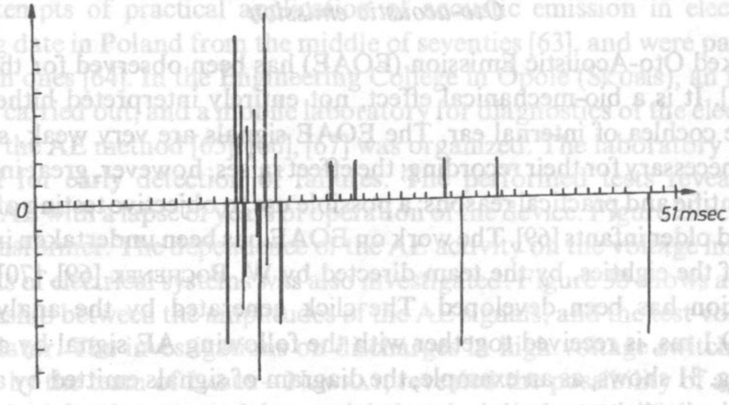


Fig. 32. Differentiation of nonlinear component of EOAE.

11. Instrumentation

The improvement of the measuring methods of AE is necessary for its successful application as a scientific tool, and for non-destructive testing of materials and constructions. The main blocks of an AE analyzer are:

— transducer of AE signals to electric signals,
— main amplifier with gain controller,
— block of high-pass, and low-pass filters,
— system of amplitude processing, and signal energy processing,
— recording block.

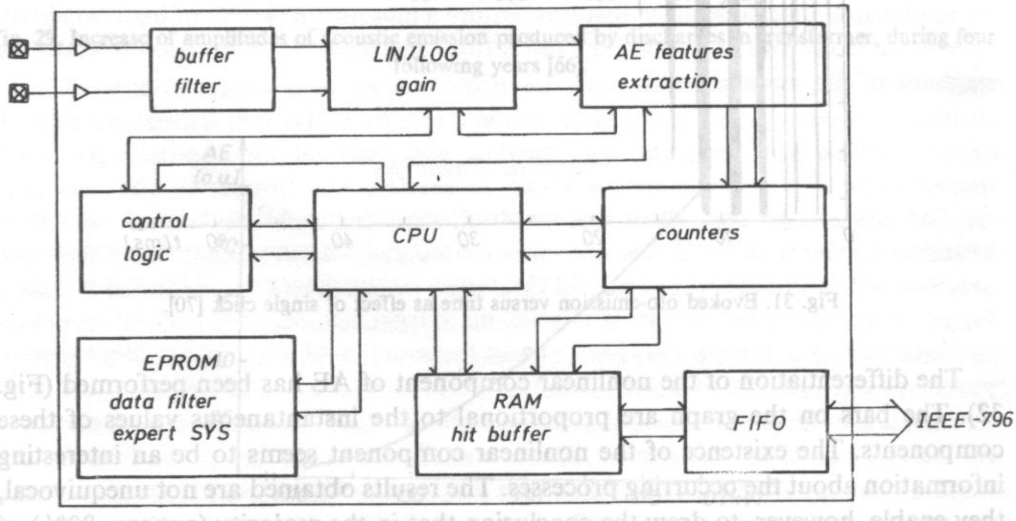


Fig. 33. Transient recorder board (TRA 2.5M) can acquire signals from an ICC output or sensor. The signal is digitized and stored in a 2.5 MB RAM and can be accessed from FFT/Transient recorder [83].

The broad-band and resonant transducersones are applied. The analysis of the AE signal parameters is usually preceded by conversion to the binary form, and is performed as a digital process, an essential parameter being the „dead" time. The block diagram of the transient recorder is shown in Fig. 33. For laboratory tests a single measuring channel is usually sufficient, while for the *in situ* measurements of technical objects multi-channel instruments are applied to simultaneous recording of AE signals. It is necessary for the location of the AE sources, for instance. Presently, numerous firms offer the instruments for the AE measurements, of different degrees of complexity: universal or adapted to special tasks.

In Poland, first designs of the analyzers of the AE signals appeared in the middle of seventies (Z. Pawłowski) [74]. Most widespread are the AE analyzers produced by the Institute of Fundamental Technological Research of the Polish Academy of Sciences; their chief designer is Z. Ranachowski [75], [76], [82]. The different variations of the analyzer of DEMA type have been produced during the last ten years. This analyzer is combined with the computer IBM PC-XT-7, and enables recording of counts with the velocity of 0.1 ÷ 100 measuring cycles per second. The further development of this lot of equipment is the three-channel analyzer (Fig. 34), which works within the band of 50 kHz ÷ 1 MHz. It enables a parallel transmission of up to 1000 bytes per second.

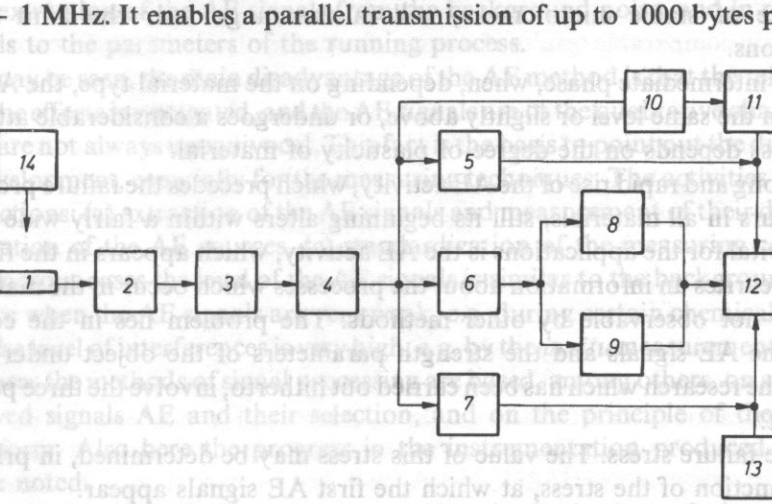


Fig. 34. Three-channel analyzer [75]. (1) converter of AE signal, (2) preamplifiers, (3) band-pass filters, (4) tunable amplifiers, (5) rms value detectors, (6) noise discriminators, (7) pulse counters, (8) delay counter, (9) sample load measuring system, (10) computer interface.

The analyzer can count pulses in two modes. In the first mode, the scalar counts pulses in the intervals 0.1, 1, and 10s, and after the end of the cycle the signals are transferred to the computer. In the second mode the instrument waits for the first signal, and afterwards the suitable channel is blocked; the instrument measures the time delay of the signals coming from the remaining two channels.

The new analyzer, which is now being designed, operates on the principle of the pattern recognition. The analyzer enables simultaneous measurements of the following AE descriptors: count sum and rate, sum and rate of events, RMS, and signal peak value, parameter of the mechanical load. The operating memory extended to 4 MB enables 500 transmissions per second. The sampling is performed at the frequency of 1 MHz.

12. Scientific and technical problems of AE method

The domains of AE application discussed above have many features in common, therefore the AE methods should be analyzed on a broad basis, taking as a reference point the common measuring techniques and fundamental research [79]. By means of the AE method, the different objects and physical processes are investigated. The most important application consists in monitoring of the AE signals during increase of the mechanical stress. As it has been discussed above, the plot of the count rate, or the count sum versus the stress has a different shape, depending on the material type. Generally however, the following three phases may be distinguished:

(1) Appearance of the first AE signals, which, depending on the material type, grow slower or faster together with the increase of the stress. It takes place after the appearance of stable micro-cracks, still in the range near the limit of elastic deformations.

(2) An intermediate phase, when, depending on the material type, the AE activity remains on the same level or slightly above, or undergoes a considerable attenuation. The process depends on the degree of plasticity of material.

(3) Strong and rapid rise of the AE activity, which precedes the failure process. This phase occurs in all materials, still its beginning alters within a fairly wide range.

Most vital for the applications is the AE activity, which appears in the first phase, because it carries an information about the processes which occur in the material, and which are not observable by other methods. The problem lies in the correlation between the AE signals and the strength parameters of the object under test. The results of the research which has been carried out hitherto, involve the three parameters of the sort.

(a) The failure stress. The value of this stress may be determined, in principle, as a linear function of the stress, at which the first AE signals appear.

(b) „Life-time" of the material. The "life-time" prediction can be drawn from the analysis of the AE signals, first of all for brittle materials.

(c) The degree of material fatigue, or the "history" of the material. Because of the structural changes, and the Kaiser effect, the differences of the AE activities can be found by comparing the new material with that used in machinery or construction elements.

The second group of the AE methods concerns the objects under normal operation conditions. The scale of such objects is very wide, and comprises for instance: high pressure vessels, shields of nuclear reactors, dams, mining tunnels and shafts. In this case the laboratory tests on samples may provide only preliminary information, while the *in situ* inspection of entire objects is necessary. It increases the range of difficulties in determination of the time correlation between the abnormalities which exist in the controlled object and the AE signals.

The experience that has been collected till now shows that the AE method enables the detection of:

(a) local increase of mechanical stress,
(b) initial displacements of the medium,
(c) leakage of gas or liquid from untight objects,
(d) local thermal disturbances.

An alarming signal may be considered to be the appearance of the first AE signals or increase of the events rate, exceeding a certain threshold value. An advantage of the AE method consists in the fact that it monitors dangerous effects earlier than other methods can do. Unfortunately, this monitoring is not entirely reliable and quantitatively determinable.

The third group of methods is connected with monitoring of the technological processes. It concerns the chemical reactions occuring due to the thermal treatment, during which the phase structure changes. The AE method enables us to indicate the beginning of the process, and to assess approximately its intensity. The main troubles lie in the extraction of the AE signals from the background noise, and in relating the AE signals to the parameters of the running process.

As it may be seen, the main disadvantage of the AE method is that the relationships between the effects investigated, and the AE signals are of the qualitative character, and that they are not always unequivocal. This fact is the basis to point out the directions of future development, especially for the measuring techniques. The activities proceed in three directions: (a) extraction of the AE signals and measurement of their descriptors, (b) calibration of the AE sources, (c) standardization of the measuring conditions.

In numerous cases the level of the AE signals is similar to the background noise, it takes place when the AE signals are very weak, e.g. during certain chemical reactions, or when the level of interferences is very high, e.g. by the *in situ* measurements in mines. In both cases the methods of signal processing are based, among others, on sampling of the received signals AE and their selection, and on the principle of their specific, iterative form. Also here the progress in the instrumentation produced in Poland should be noted.

Another direction of development consists in limitation of the sources of disturbances, for instance in the testing machines.

The records of the AE signals, plotted against the time axis, especially these coming from the continuous emission, look seemingly chaotic, therefore it is essential to apply a proper technique of the signal processing to obtain the parameters which are correlated with the physical quantities of interest. In the literature [61] the proposals of several descriptors of AE signals can be found. Also interesting are the proposals of the Polish authors concerning, for example, determination of the energy related to a single event [48] and the analysis of usefulness of the AE descriptors [88]. Nevertheless, on the grounds of the work done as yet, it is difficult to decide which of the descriptors might be the most commonly used; the question is still open.

The acoustic–electronic channel for the AE signal transfer contains so many elements, transmission coefficients of which are difficult to determine, that assigning the absolute values to the AE signals appears to be a very difficult task. Determination of such a value is, on the other hand, without practical significance, because a comparison of the measured signals with the simulated AE sources was an object of research long since [71], [72]. The most frequently applied simulated sources are:

— stream of gas,
— breaking of capillary or pencil lead,
— falling ball,
— standard electromagnetic or electrostatic transducer,
— laser pulse.

The comparative analysis of the first three types of the simulated sources was also performed in Poland [89]. These sources are in common use, each of them having its own advantages and defects. The trouble is that the standards used in different laboratories do not always correspond to each other, while in reports and papers the references concerning the standards used are usually not included. So the wide international exchange of experiences, as well as spreading of the best standards among the laboratories throughout the world, would be highly desirable.

To obtain comparable results of testing, standardization of the reference simulated sources together with the intermediate blocks will not be fully satisfactory. The standardization of the measuring conditions is also desirable. During laboratory strength measurements the dimensions of the samples are usually in accordance with the obligatory standards, and it does not create any problem. Instead, the acoustic-electronic channel is developed in a very individual manner, and certain standardization would be useful. It might encompass:

— coupling media,
— transmission characteristics of the transducer,
— characteristics of filters and gates,
— determination of discrimination levels of AE signals.

Standardization of the references simulated sources and terminology has been initiated by the European Working Group on Acoustic Emission [78], the work is continued.

When selecting particular descriptors, their parameters should be determined.

The above mentioned necessity of switching from the qualitative observations to the comparable, quantitative measurements relates to the need of undertaking certain research. It should be focused, among other things, on:

(a) Collecting more data concerning the relationship between AE and stress in various materials. The statistic analysis of the data will enable a better determination of the connection of AE with the mechanical strength of material [73].

(b) The relationship between the original AE signal and the value obtained during the measurement. In spite of numerous attempts, the through knowledge of the mechanism of AE signals generation remains open. It is of great cognitive importance to have a AE method capable of providing unique information about the physical micro-processes that take place in various materials and media.

The investigations might concern:

(a) Generation of AE by groups of dislocations;

(b) Relationship between appearing of the plastic zones at micro-cracks and the AE signals;

(c) The effect of the changes of material microstructure, together with the phase transitions, on the AE;

(d) Generation of the AE signals during chemical reactions.

The AE signals distinguish themselves by a great variety of time-dependence. The general division into continuous and burst emissions is not satisfactory. A more detailed classification of the AE signals coming from different sources, based on the selected descriptors, would be desirable.

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