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THE DEVELOPMENT OF DEFORMATION PROCESS IN CARBON FIBER REINFORCED PLASTICS AND METALS ON ACOUSTIC EMISSION DATA

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There exists some correlation between deformation curve type and characteristics of acoustic emission flow. It is observed nonhomogeneous development of micro structure changes in the different parts of the specimens on diverse stages of deformation. The collective effects on various scale levels are observed in some local volumes at the concluding period of loading. It is shown that a process of the fracture occurring in some micro volumes of strained composite of the type of carbon fiber reinforced plastic (CFRP), takes place on a few levels of velocity and development times.

1. Introduction

A composite is subject to diverse micro mechanisms of damage, some of which contribute to its safe life time, ultimate strength or toughness. If one wishes fully to utilize the properties of these advanced materials, it is essential to understand the dynamic of each mechanism of damage and also the effect of constitutent scaling and interaction on the macro-response of the material. The fracture toughness of composites is a result of various mechanisms such as crack formation, fiber-matrix debounding and subsequent pullout. Under monotonic loading on a composite, small cracks form in the matrix normal to the direction of loading, what is specially seen in undirectional composites loaded in the direction of the fibrous reinforcement. This causes the transfer of load to the fibers with increasing shear stress, eventually producing the failure of the bound between the fiber and the surrounding matrix. The cylindrical crack at the interface propagates from the initial matrix crack, creating debounding along the fiber.

Each kind of cracking causes the creation of acoustic emission. Development of acoustic emission (AE) method of material and structure testing leads to more broad its using for studying fracture mechanisms of solids and especially of composites. The knowledge of the structure transformation in strained metals in real time gives a possibility to forecast the safe endurance and ultimate strength as well as makes easier searching for the materials with better characteritics. From this point of view undirectional composites of the type of carbon fiber reinforced plastic (CFRP), are very convenient model objects for the investigation and on the other hand they create a new kind of structural materials with great application and development possibilities.

2. Specimens and measurements

The investigations were made using the specimens $160 \times 7 \times 1$ mm^3, cut off from the composite plates, undirectionally reinforced by carbon fibers. Two ceramic piezoelectric transducers were used with resonance frequency 400 ± 50 kHz. They were attached on the specimens on the distance $80-100$ mm apart. Signal recording and data converting systems were applied, based on the processors E-60 and HP-9835A. Discrimination level was 50 μV, and single carbon fiber fracture produced an AE signal of the amplitude $90-100$ μV.

The specimen straining under growing loading F was taken with a constant velocity 0.22 mm/min of testing machine holders. All experiments and measurements were performed at the Ioffe Physico-Technical Institute, St. Petersburg.

3. Study effects and discussion

Composite of the type undirectional CFRP makes possible to solve in the first approach an "old" problem of fiber breaking consequences and by this the role of appearing then microcracks which precede the formation of macrocracks, i.e. in shaping of macro-fracture. According to [1], a final destroying of fiber composite, the main component of which is reinforcing carbon fiber surrounded by plastic matrix, occurs due to such a big concentration of fiber cracks that external stress in working section of the specimen achieves a critical value. According to the second extreme point of view [2, 8], catastrophic destroying can take place as a result of cracking of a poor few neighbouring fibers, if this event leads to a great concentration of local stress. However, the direct observation of the development of microcracks done *in situ* in a chamber of scanning electron microscope [3], has shown a lack of active mutual interactions of microcracks in almost the whole time when the material is under an external loading. In real solids appearing the micro-plasticity, mutual interaction of microcracks takes place only at the first moments ($10^{-2}-10^{-1}$ s) after the creation of new microcracks, as later they deteriorate due to stress relaxation. Acoustic emission method gives the opportunity for solving this serious topic of fracture physics and mechanics in real composites and/or structures, and not only in model situations [3]. It seems that such an information can be delivered by statistical analysis of measurement of AE event rate in particular local microvolumes of greater objects.

A graph of changes in event rate $\dot{N}(t)$ as a function of time t of tensile loading action on the whole of specimen is shown in Fig. 1a. This traditional way of result presentation shows a spontaneous increment of event rate in the final stage of loading

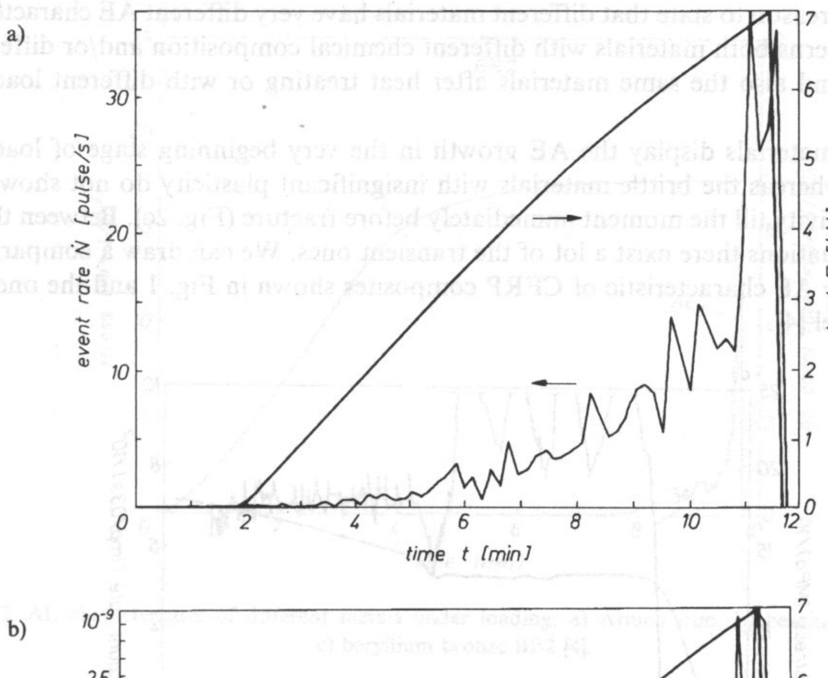
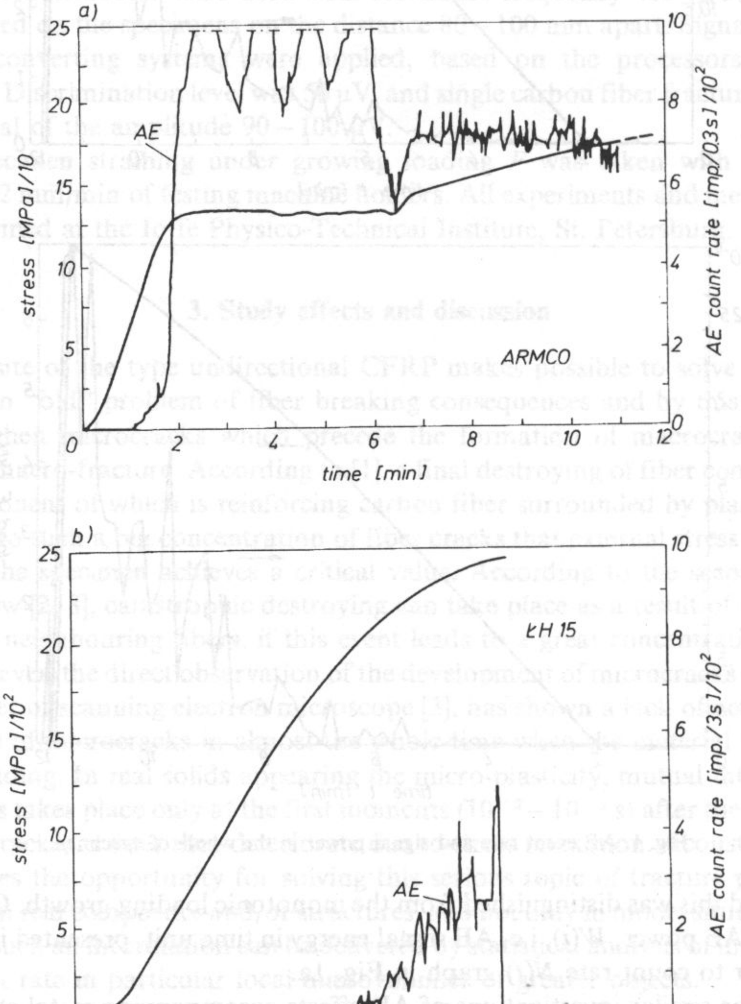


Fig. 1. AE event rate and signal power in the whole of specimen.

increase and this was distinguished from the monotonic loading growth. Character of changes in AE power, $W(t)$, i.e. AE signal energy in time unit, presented in Fig. 1b, is very similar to count rate $\dot{N}(t)$ graph in Fig. 1a.

From the similar investigations of AE effects accompanying metal straining it is well-known [4] that AE characteristics are very different, depending on the kind of crystal space lattice and the structure of the particular materials. The experiment results give reason to state that different materials have very different AE characteristics. It concerns both materials with different chemical composition and/or different structure, and also the same materials after heat treating or with different loading history.

Plastic materials display the AE growth in the very beginning stage of loading (Fig. 2a), whereas the brittle materials with insignificant plasticity do not show the acoustic activity till the moment immediately before fracture (Fig. 2c). Between these extreme situations there exist a lot of the transient ones. We can draw a comparison between the AE characteristic of CFRP composites shown in Fig. 1 and the one for bearing steel [4].



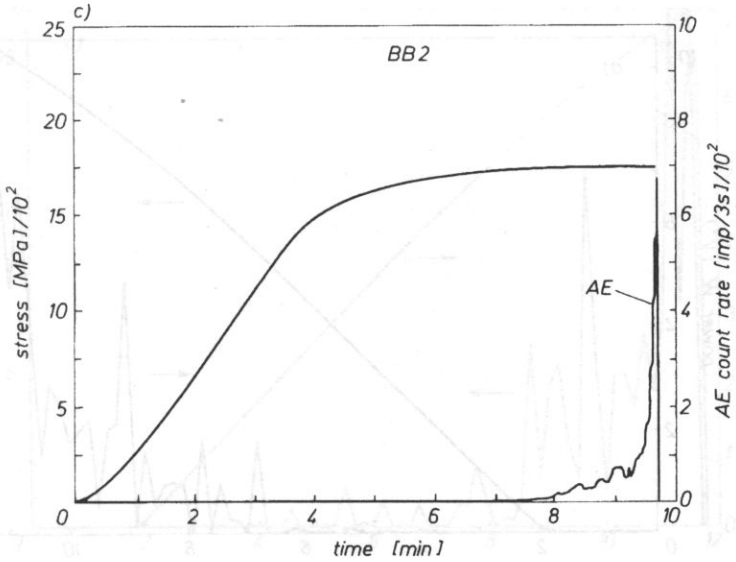
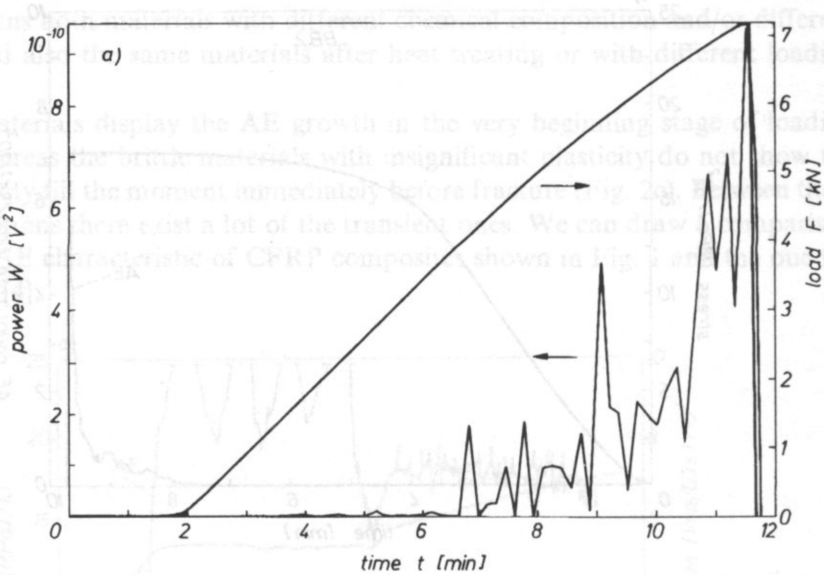


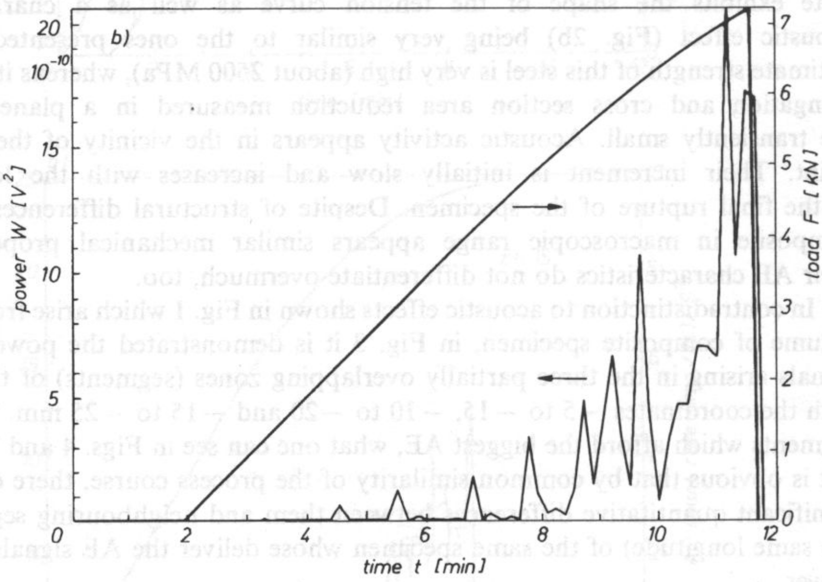
Fig. 2. AE characteristics of different metals under loading: a) Armco iron, b) bearing steel ŁH15, c) beryllium bronze BB2 [4].

Such a bearing steel in the thermally treated and low-temperature tempering state exhibits the shape of the tension curve as well as a character of the acoustic effect (Fig. 2b) being very similar to the ones presented in Fig. 1. Ultimate strength of this steel is very high (about 2500 MPa), whereas its irreversible elongation and cross section area reduction measured in a plane of fracture are transiently small. Acoustic activity appears in the vicinity of the offset yield point. Their increment is initially slow and increases with the load increase to the final rupture of the specimen. Despite of structural differences, the CFRP composite in macroscopic range appears similar mechanical properties. Thus, their AE characteristics do not differentiate overmuch, too.

In contradistinction to acoustic effects shown in Fig. 1 which arise from the whole volume of composite specimen, in Fig. 3 it is demonstrated the power of the AE signals arising in the three partially overlapping zones (segments) of the specimen, with the coordinates -5 to -15, -10 to -20 and -15 to -25 mm. They are the segments which afford the biggest AE, what one can see in Figs. 4 and 5. From Fig. 3 it is obvious that by common similarity of the process course, there exist also the significant quantitative differences between them and neighbouring segments (with the same longitude) of the same specimen whose deliver the AE signals of different power.

The comprehensive graph of signal power $W(L,t)$ from the particular specimen segments is shown in Fig. 4; they are gotten in the function of length coordinate L and loading time t. Non-regularity in AE distribution as the process bonded with fiber fracture can be clearly seen, both in the function of time (loading) and of specimen


a)
10^{-10}
power W [V²]
load F [kN]
time t [min]


b)
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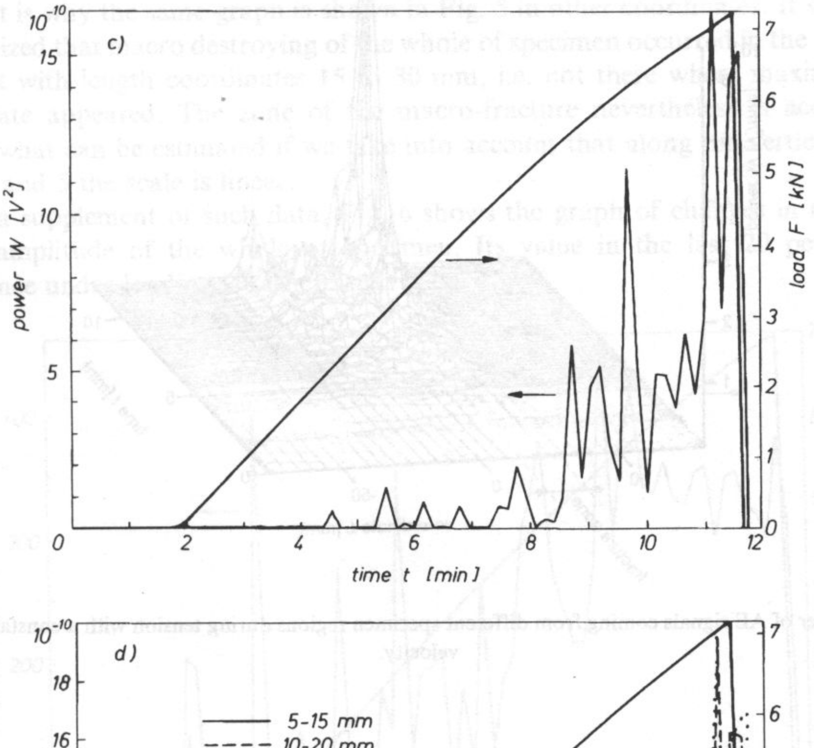

Fig. 3. AE signal power in the particular specimen segments: a) -5 to -15 mm; b) -10 to -20 mm; c) -15 to -25 mm; d) -5 to -25 mm — summary graph.

length co-ordinate. In the last stage of the process, the AE increment is very fast, what is expressed by local inclination of the AE graph, and it is rather difficult to estimate quantitative the process development in the final its moments.

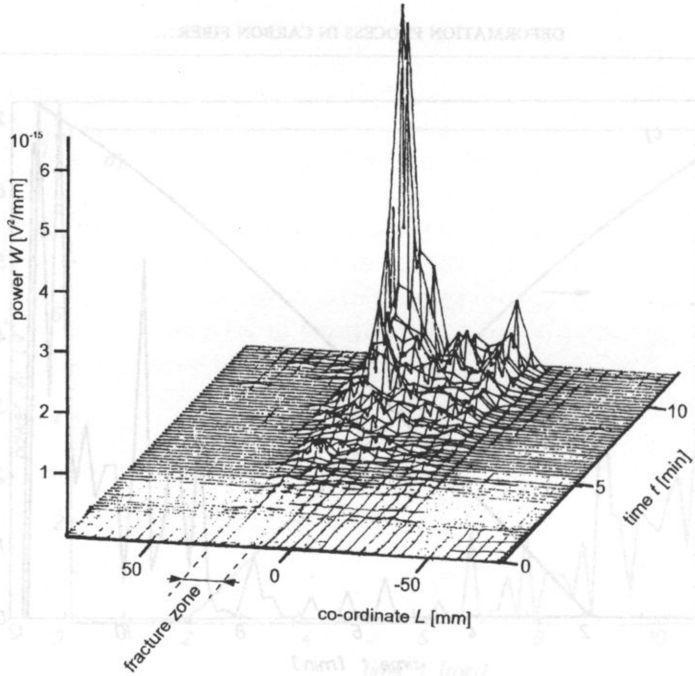

Fig. 4. Power of AE signals coming from different specimen regions during tension with a constant holder velocity.

Fig. 5. AE event rate from different specimen regions during tension with a constant holder velocity.

That is why the same graph is shown in Fig. 5 in other coordinates. It should be emphasized that macro destroying of the whole of specimen occurred in the specimen segment with length coordinates 15 to 30 mm, i.e. not there where maximum AE event rate appeared. The zone of the macro-fracture nevertheless is acoustically active, what can be estimated if we take into account that along the vertical axis in Figs. 4 and 5 the scale is linear.

As a supplement of such data, Fig. 6 shows the graph of changes in mean AE signal amplitude of the whole of specimen. Its value in the last 20 per cent of endurance under loading is rather steady.

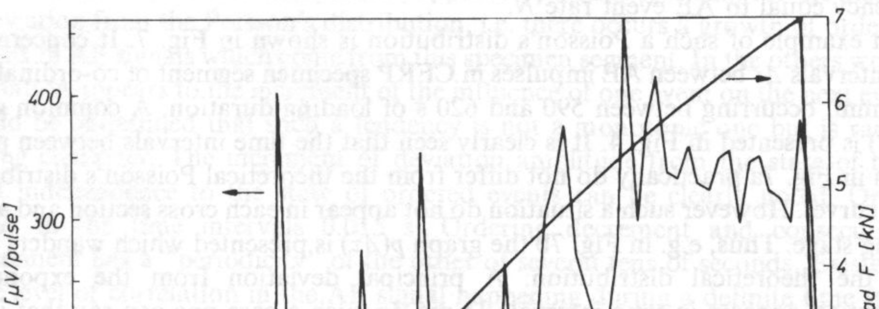

Fig. 6. Mean amplitude of AE signals coming from the whole of specimen.

From the comprehensive study of the problem it follows that in CFRP composite do not appear any univocal AE parameter changes of the evident shape, which in defined place and time could be a prelude to cracking occurrence, and thus they could not constitute a reliable signaler of destroying danger. However — as it will be shown below — in the course of specimen deformation in defined conditions some peculiarities in the behaviour of particular specimen segments can be ascertained. In order to attain this, let us consider the distribution of time intervals $\Delta\tau$ between the AE pulses in the particular specimen segments at different moments of loading process (i.e. by different loading values).

For correct statistical analysis the appropriate sets should be sufficiently representative (70 to 100 events), and the process itself ought to be stationary, i.e. the changes in AE signal flux as a rule ought to be not greater than 20 per cent of stationary level.

In the case of full independence of signal appearance it can be an exponential or a Poisson's distribution. The Poisson's distribution is a frequency distribution which often applies when the probability of an event happening is extremely small. Suppose that in a large number of trials the probability of an event happening is p, where p is small, but the average number of events in any given set of trials is a finite number. If Poisson's distribution applies, the probability of event occurrence is

$$p(\Delta\tau)=me^{-m\Delta\tau}, \tag{3.1}$$

where p is the probability density, $\Delta\tau$ is time interval between the events and m is event frequency equal to AE event rate $\dot{N}$.

An example of such a Poisson's distribution is shown in Fig. 7. It concerns the time intervals $\Delta\tau$ between AE impulses in CFRP specimen segment of co-ordinates 10 to 20 mm, occurring between 590 and 620 s of loading duration. A common graph $W(L,t)$ is presented in Fig. 4. It is clearly seen that the time intervals between pulses shown in Fig. 7a practically do not differ from the theoretical Poisson's distribution (solid curve). However such a situation do not appear in each cross section and at any loading stage. Thus, e.g. in Fig. 7b the graph $p(\Delta\tau)$ is presented which wanders away from the theoretical distribution. A principal deviation from the exponential distribution appears in time intervals 15 ms. In such a case one can say that in the Poisson's distribution of the sets some ordering appears [5], although commonly in time intervals greater than 15 ms the events in the considered event flux are independent. As a quantitative measure of the deviation from Poisson's distribution (i.e. an ordering measure) may serve [6] the coefficient of ordering

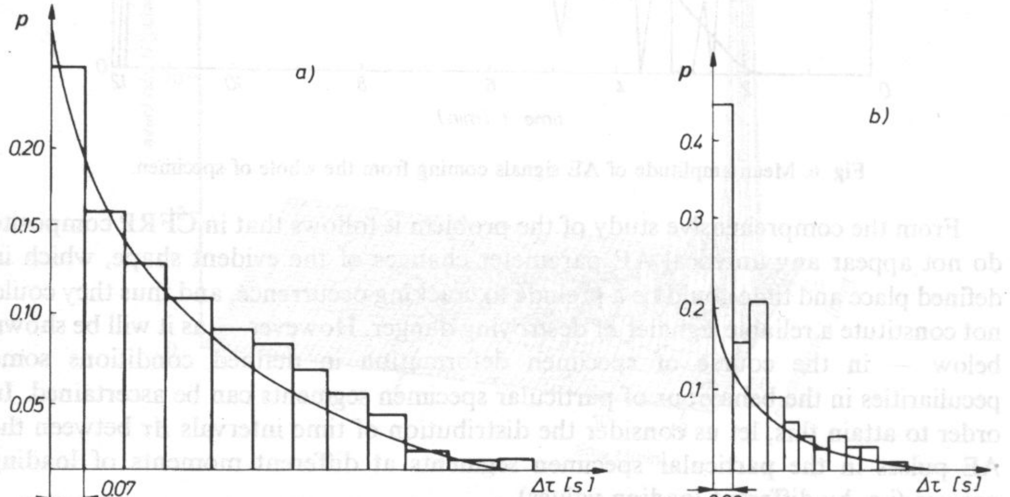

Fig. 7. Probability distribution $p(\Delta\tau)$ of time intervales $\Delta\tau$ of AE signal happening in the segment (−10 to −20 mm) loaded during: a) 590−620 s; b) 670−690 s.

$$\delta=\left|1+\frac{\overline{\Delta\tau}}{\sigma_\tau}\right| \tag{3.2}$$

where $\overline{\Delta\tau}$ is the mean time interval between the events in a given event set and σ_τ is the medium square deviation. It became evident that such an ordering leads to the interesting and more conclusive information about the destroying process development than the one illustrated by three-dimensional graphs $W(L,t)$ in Figs. 4 and 5.

Figure 8 presents the deviation degree of the considered distribution from the Poisson's distribution. It seems that during the final 25 per cent of loading time in the fracture zone of the CFRP composite it appears a peculiar tendency for the increment of deviation from the Poisson's distribution, i.e. there occurs a growth of ordering in the flux of AE signals which come from this specimen segment. In the others words an inclination appears to the increment of the influence of one event on the next event. It should be underlined that such a tendency is not a monotonic one but is rather of pulsing character. The increment of deviation amplitude from the state of mutual event independence to the state of ordered events can be clearly noted. Ordering occurs in the time intervals 0.015 s. Ordering decrement and consecutive its reincrement has a "periodicity" of the order of several tens of seconds. Existence of some level of correlation in the AE signal happening during a definite time (tens of seconds) even by growing external loading can be an evidence that in a given local volume it appears the decrement of elastic strain energy concentration. The decrease of local stress level as a result of more rough micro structure transformation temporally diminishes driving force of this process. To a certain degree such a state can be however induced also by relaxation process taking place in the neighbouring specimen segments. Indeed, fracture zone and neighbouring segment (5 to 15 mm) with the great AE activity as a rule are in the anti phase (see mutual positioning of the

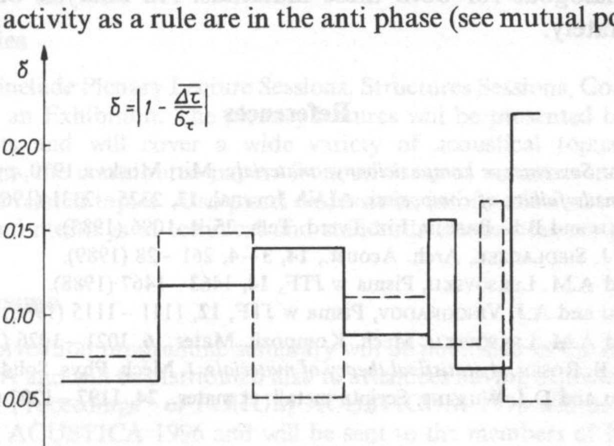

Fig. 8. Changes in coefficient δ in fracture zone (15 to 30 mm) and in neighbouring zone (5 to 15 mm) in final ca. 120 s loading stage (—— fracture zone, ----- active zone).

solid and dotted lines in Fig. 8 and the differences between them). It can be signified that in the final moment of a mutual interaction this anti phase frequently is the most visible and quantitatively the most significant.

Statistical analysis of time intervals between the successive pulse happening shows the existence of specific ordering, i.e. the mutual connection between the events in millisecond intervals — in the range from 0 to 100 ms. Besides the collective effects in such a short time intervals, an analysis of the parameter $\delta(t)$ justifies the existence of collective effects in much greater time intervals — of several tens of seconds, i.e. there appear also the relaxation process in time interval 10^3 – fold longer than in the former case.

On the ground of the general circumstances one can suppose that in heterogeneous solids there ought to appear at the lowest estimate one more time scale of mutual effects, i.e. on the load of sound velocity. Such different time scales of the plastic deformation process in different degree influence the formation of the state which precedes the fracture in this strongly isotropic composite of high strength. One can suppose that knowledge of the sequence of microstructural transformation process and transition mechanism from one scale of group effects to another one could be helpful in searching for a manner of process shaping and safe endurance forecasting of this kind of materials.

It is worth to underline that similar phenomena can occur not only in composites but also in metals with similar AE characteristics. Thus, e.g. in bearing steel ŁK15, graph of which during the monotonic tension is presented in Fig. 2b, is like in CFRP composite, i.e. the strong AE signals appear only in the loading stage immediately before the destroying. The discussed problems and graphs such as presented in Figs. 7 and 8 are analogous for both these materials. An analysis of the topic will be presented separately.

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