acta mechanica et automatica, vol.4 no.4 (2010)

APPLICATION OF ACOUSTIC EMISSION IN FATIGUE FRACTURE DIAGNOSTICS

Valentyn SKALSKY[*], **Pavlo HALAN**[*]

[*]Karpenko Physico-Mechanical Institute of the National Academy of sciences of Ukraine,
Naukova str., 5, Lviv, Ukraine, 79060.

skal@ipm.lviv.ua, galanpol@ukr.net

Abstract: The most important peculiarities of the acoustic emission under fatigue loading are reviewed. Dependences of the AE signals and parameters of the growing fatigue crack on the basis of an existing literature source review are established. An essential role of the correlation for determining the crack growth rate in the relation between the AE parameters and crack parameters are shown. An energy approach for determination of cycle quantities till the initiation of a crack is proposed.

1. SOURCES OF AE UNDER FATIGUE FRACTURE

In the presence of a fatigue crack during one loading cycle there is a possibility of appearance of a complex aggregate of the AE signals. To describe the particularity of appearance of one or another signal component, it is necessary to consider more in detail the processes, which lead to the AE signals in the presence of a fatigue crack in a solid. To those processes one may referred: creation and growth of a plastic deformation area at the tip of a crack; an increase in the crack length (square); the crack closure (Drobot and Lazarev, 1987; Penkin and Terentev, 2006).

It is well known that a crack growth in constructive metal materials is accompanied by local plastic deformation. Its main components - sliding and twinning – generate the AE waves. Usually, the principal contribution to the emission of elastic waves is made by that part of the material, which within a certain range of relative deformation, transfers to the plastic condition. An unloading and reloading of this volume to the preceding maximum loading level in consequence of Kaiser Effect (Drobot and Lazarev, 1987; Tensi, 2004) result in – a sharp decrease in wave emission. However, under the cyclic loading, even when the maximum cycle loading level is permanent, there is a factor, which contributes to an increase in AE – that is the involving into the present deformation's interval of a new volume of the material, previously deformed outside the given interval. This is achieved, when two conditions are satisfied. The first one is accumulation of the plastic deformation under constant crack length as a result of an unclosed hysteresis loop during the elastic-plastic deformation. The second one is the crack development, i.e. the crack length (square) increase.

The first condition is typical of cyclical off-strengthened materials under the soft loading working condition. Such materials during asymmetric cycles have accumulation of the plastic deformation from a cycle to cycle. Under those circumstances there is a development of a "neck" in the specimen and fracture is of the same character as under the static tension. This effect is absent in cyclical strengthened materials. During the development of a crack a new volume of the material is involved into the plastic deformation. Since an increase in the crack square is located at the maximum of the cycle loading, the progress and growth of the plastic deformation's region and correspondingly the appearance of the AE signals from plastic deformation will be located at those maximums. An increase in the crack length also causes AE signals, which are located at the same places of cycle loading.

According to the research works (Mitchell and Egle, 1977; Mitchell at al., 1972) there was found out one more peculiarity of the AE signals. The two types of AE were established: the first one appears at the points of maximum rate in the cycle, and the second – burst emission, which appears at the point of curvature's maximum and minimum. The first type is connected with crack initiation, and the second one – with crack growth. In works (Shyrjajev and Kamyshov, 2002; Pavelko and Ozolinsh, 2002) the AE signals were divided into discrete high-range and continuous low-range components. The latter was caused by plastic yielding, and the discrete AE - by the growth of the existing crack.

A lot of experimental investigations (Drobot and Lazarev, 1987; Penkin and Terentev, 2006; Pollock, 1989) are devoted to the contact crack closure phenomenon. For a normal tear it starts when a loading falls down to zero and evolves under compression. It is well known, that a crack closure begins earlier – during a decrease in the cyclical loading. Emission waves under these circumstances are caused by the two processes – dynamic blows and mutual friction of the crack banks. If one supposes, that blowing and friction are just elastic processes, then signals generated by them can not be referred to the AE containing information on fracture, since there are not any reconstructions of the material structure in the contact area. However, a typical kind of fatigue break testifies to the presence of the local plastic friction deformation there. Thus, an aggregate acoustic signal of the crack closure phenomenon is a mixture of the useful AE signals and acoustic noises resulting from the dynamic elastic crack banks blowing. Frequency's spectrum of these noises is limited and does not reach to the working frequency's band, which is used while measuring AE. In this connection a number of the AE signals can be referred to informative signals, and it is possible to define them as AE from crack friction.

In works (Harris, 2007; Harris and Dunegan, 1974) AE from a crack closure was interpreted as a criterion of the presence of a crack growth during the cyclic loading.

In the given work we will focus on the generation of the AE waves resulting from the processes of plastic yielding and crack growth. Considering this we should keep in mind the fact that AE signals from the crack closure phenomenon can be easily separated from other AE signals with the help of time and frequency selection (Drobot and Lazarev, 1987; Penkin and Terentev, 2006).

If one registers the components of plastic deformation and crack growth only, then it is possible to mention their two typical properties. First of all: the signals are absent in certain cycles (under the given apparatus sensitivity). Thus, all the loading cycles can be divided into active (with the AE signals) and passive (without them). Secondly, in the active cycle both the single impulses and groups of impulses may arise. These particularities represent a disproportional development of the fatigue crack and possibilities of its several jumps in one cycle in the region of the maximum loading.

2. DEPENDENCE BETWEEN PARAMETERS OF THE AE AND CRACK PARAMETERS

The AE usage opportunities for the discovery and evaluation of crack parameters are fined by the presence of relations between the crack parameters and the emitted waves. The first of such relations are obtained in Morton et al. (1974). Investigating the aluminium alloy 2024 the authors obtained a good dependence between the total quantity of the AE signals and the rate of the crack growth, as well as the stress intensity factor K (k-factor). Using Paris equation for determining rate of the crack growth l' as follows:

$$l' = C\Delta K^{q}, \tag{1}$$

where ΔK – a changing interval of k-factor; C, q – material parameters.

To obtain a better data correlation during experiments with different values of cycle asymmetry $R = K_{\min}/K_{\max}$ and for maximum k-factors $K_{\max}$, which approached the critical value K_c, the empirical Forman equation for a crack growth rate was used

$$l' = \frac{C_1 \Delta K^{p}}{(1-R)(K_c - K_{\max})}, \tag{2}$$

where C_1, p – material parameters.

Haris and Dunegan (1974), investigating the growth of a fatigue crack in the aluminium alloy 7075-T6 and in steel, considered that $\dot N$ is directly proportional to the energy releasing during the crack growth ($J'=B/E(\Delta K/(1\text{-}R))^2 l'$). Here J' – energy; B – specimen thickness; E – Young's modulus. To evaluate the velocity of AE the formula $\dot N = CJ'$ was used, where $\dot N$ – velocity of AE counting; C – material constant.

In work (Lindley et al., 1978) it is assumed that AE depends on the two components: the above described energy, realising during the crack growth, and also on the processes of plastic deformation and fracture in the plastic region. Therefore, the velocity of the total measurement of the AE was given in the form of $N'_{Total} = N'_1 + N'_2 = (C_1 + C_2) \cdot J'N'_{Total}$, where N'_1 – velocity of AE counting under crack extension; N'_2 – velocity of AE counting under the processes of plastic deformation; C_1 – direct contribution of crack extension; C_2 – contribution of plastic deformation activity. To describe the crack growth rate a well known equation (Lindley et al., 1978) was applied:

$$l' = C_r \left(\frac{\Delta K^4}{\sigma_1^2 \left(K_c^2 - K_{\max}^2\right)} \right)^{r}, \tag{3}$$

Here σ_1 – strength limit; $r = 0{,}75$ for steels. In the work an essential difference between the total AE counting velocities for different steels and alloys is also pointed out, this difference equals to almost 4 orders of magnitude. Besides, there was an investigation of the cycle asymmetry effect on the AE velocity. It was established that the AE velocity increases with the increase of R. Also there was shown a decrease in crack growth rate near the maximum loading when an overloading took place. In the given work and also in Hreshnikov and Drobot (1976) it was established, that magnitude of the total AE counting N is proportional to the plastic region volume. The authors of the work Nagornyh and Sarafanov (1990), regarding the total AE counting as that being proportional to the plastic region and haven taken an increment of the crack as the magnitude of Irvin's correction $r = K_I^2/2\pi\sigma_T^2$, obtained the relation between the AE counting velocity and crack growth rate:

$$\dot N = BK_I^2 \frac{dl}{dt} \cdot \tag{4}$$

In works (Gerberich and Hartbower, 1966, 1966) is shown, that there is a possibility of quantitative relation between the AE amplitude and the crack size increase. In work (Drobot and Lazarev, 1987) it is considered, that amplitudes of the dynamic displacements A_{ijn}, caused by an increase in the crack length (square), do not essentially exceed the corresponding increments of the static displacements Δu_{ijn} at the tip of the crack. In the mathematical form it can be given as:

$$A_{ijn} \approx \Delta u_{ijn} \tag{5}$$

An elementary act of the crack's growing-up consists in the increase in its length by a small magnitude Δl. At a sufficiently high rate of the process (while jumping) the AE impulse is generated. It is also considered, that under fatigue loading an increment of the crack Δl locates near the maximum loading. Then Δl takes sense of the crack length increment per cycle, i.e. crack growth rate $l' = dl/dn$, where n – the number of loading cycles. Taking this into account, the dependence (5) can be written as:

$$A_{ijn} = M_{ijn}(\lambda) \frac{p_{j\max}^2}{J\sigma_p} l', \tag{6}$$

Here $M_{ijn}(\lambda)$ – a certain function, which form depends on the type and configuration of the crack, its orientation relatively to coordinates axes, geometrical parameters of the object, and peculiarity of the applied loading [6]; λ – crack length, relative to the width of flat specimens; p_{jmax} – component of the outside specific maximum loading corresponding to the crack's type; J – shear modulus; σ_p – limit of proportionality.

During the appearance in the cycle of several subsequent crack jumps the dependence (6) remains, if l' implies the total length of these jumps, and A_{ijn} stands for equivalent amplitude a_{ijn}.

Thus, under other equal conditions the amplitude of the AE signal is proportional to the crack length. It can be also represented by the parameter λ.

If a law of the development of the fatigue crack is known, then the right side of (6) can be given the form of that having the only parameter – the crack length. To do so one should put into the equation (6) one of the equations (1), (2) or (3). In that way we will obtain a correlation between the amplitude and the crack growth.

Generalizing relations between the AE parameters and the crack parameters and resulting from the physical nature of the phenomenon and a general scheme of the measurement of the AE parameters, in work (Drobot and Lazarev, 1987) there was built a diagnostic model with the help of the operator equation:

$$E = P_E\left\{P_A\left[P_B\left(T\right)\right] + Ш_A\right\} + Ш_E \tag{7}$$

Here T – vector of the crack state, E – AE signal vector; P_E, P_A, P_B – operators of the electrical, acoustic and entrance conversion correspondently; $Ш_A$, $Ш_E$ – vectors of the acoustic noise in the control object and noise of the electronic equipment. As a result of the absence of the general solution to the problem of the dynamic elastic-plastic deformation theory, solid acoustics, mechanical-electrical conversion of the vibration, etc, it is not possible to define strictly operators in equation (7). So, a number of hypotheses are assumed, simplifying mutual dependencies between the properties of the object, the AE sources and its signals. Among them there are a simplification of the geometrical characteristics of the crack, the absence of noises – an ability to cut noises and select the useful AE signals with the help of active methods or equipment means (Bezimjany and Halenko, 2007; Drobot and Lazarev, 1987; Penkin and Terentev, 2006; Pollock, 1989; Skalsky and Koval, 2005). The form of operators in formula (7) also essentially depends on the choice of state parameters and informative parameters of AE. The simplification can be obtained, if one uses parameters not connected (or slightly connected) to the form of the acoustic signals.

3. DETERMINATION OF CYCLE QUANTITIES TILL THE INITIATION OF A CRACK BY THE ENERGY APPROACH

Following the previously discussed peculiarity of the relation between the AE parameters and crack parameters, it should be pointed out that the essential role of correspondence between these parameters is played by the correlation for determining the crack growth rate. It is well known that one of the widespread approaches to the research of the fatigue macro-cracks is the strength criterion. In the strength criterion the crack growth velocity is described by the function of k-factors (K_I, K_{II}, K_{III}). Besides the strength approach, the deformation approaches also applied, which is based on δ_c – model. The deformation criterion is used, when the plastic region at the crack edge is of size as the solid and the defect.

The described criteria are sufficiently effective when the loading cycle is stable (an overloading and a frequency change are absent). As well as the history of the material deformation and crack extension are not taken onto account. Then k-factors or magnitudes of the crack disclosure are fatigue fracture invariants.

For a detailed description of the pre-critical fatigue crack growth, when a change of the cycle loading and its amplitudes possible, the history of deformation, crack extension and the effect of the aggressive environment are taken into account. For this purpose energy approaches are to be used.

For the first time such an approach was offered by Cherepanov. In its basis there is a hypothesis of constancy of the dissipative energy during the creation of a unit of the fatigue fracture surface and the first thermodynamics law of energy balance. Finally Cherepanov approach also can be transformed to the representation of the crack growth rate as a function of K_I, but in a more detailed form. A more perfect approach is given in work (Shata and Terlecka, 1999). Here as the basis the first thermodynamics law is taken, according to which after N loading cycles the following energy balance condition is fulfilled:

$$A + Q = W + K_e + \Gamma \tag{8}$$

where A – work of inner power P per N cycles; Q – heat magnitude, brought to the solid per N loading cycles; K_e – kinetic energy of the solid; W – deformation energy after N loading cycles; Γ – fracture energy of the solid with a change of its square by magnitude S.

Through the differentiation of the (8) by the cycle quantity N, was pass to velocities, and introducing a number of simplification, we obtain the equation for crack square growth velocity

$$\frac{\partial S}{\partial N} = \frac{\partial W_C}{\partial N} \Bigg/ \frac{\partial\left(\Gamma - W_S - W_r\right)}{\partial S}, \tag{9}$$

where W_c – energy of a cyclic change of deformation; W_s – static component of the energy, which changed during crack growth; W_r – energy of plastic deformation of the material before the beginning of the cyclic loading. Having determined in the relation (9) energy magnitudes according to the results of work (Shata and Terlecka, 1999), we come to the equation for definition of the crack growth rates, in the right side of which only material constants and k-factors will be present.

An investigation of the energy approach and its application to the various problems of determining a fatigue crack growth rate are carried out in works (Andrejkiv and Lischyncka, 1999, 2000; Andrejkiv and Rudavsky, 2004; Andrejkiv and Kit, 2006; Terlecka and Kit, 2004). Among the principal results there the following:

- Description of the fatigue crack growth equation in the non-homogeneous plates (Andrejkiv and Lischyncka, 1999) (the kinetic crack growth equations in plates which are non-homogeneous in relation to the resistance to fracture were formulated; taking into consideration the preceding plastic deformation).

- Calculation model of the initiation of the fatigue crack near the notch filled with hydrogen (Andrejkiv and Rudavsky, 2004) (a calculation model of the fatigue crack initiation using the energy approach was built. The influence of hydrogen was modeled by decreasing critical deformation according to the linear law).
- Energy approach to determination of the pre-critical growth of the fatigue crack under loading with two frequencies (Andrejkiv and Kit, 2006) (loading with two frequencies: one with high amplitude and low frequency was taken into account, another with low amplitude and high frequency).
- Application of the energy approach to evaluation of the residual durability of thin-walled elements with surface cracks (Terlecka and Kit, 2004) (a formula for calculation of the number of cycles to through-extension of the crack in a thin plate was obtained).
- Residual durability of elements, which are non-homogeneous by the mechanical characteristics (Andrejkiv and Lischyncka, 2000).

4. CONLUSIONS

Under a fatigue loading the AE is characterized by a number of properties an investigation of which can provide a clue to solution of different essential problems of fracture mechanics.

Following to the reviewed literature sources, parameters of the AE particularly correlate with rate of the fatigue crack growth. Among different theoretical criteria of the crack growth rate determination, energy criterion is the most complete. It includes all factors that exist under fatigue fracture. Thus, there is a great interest in further theoretical-experimental investigations of the AE signals application for interpretation of fatigue fracture mechanisms and their combination with energy approach relations obtained in works (Andrejkiv and Lischyncka, 1999, 2000; Andrejkiv and Rudavsky, 2004; Andrejkiv and Kit, 2006; Terlecka and Kit, 2004).

REFERENCE

1. **Andrejkiv O.E., Lischyncka M.V** (2000), Zalyshkova dovgovihnist elementiv, neodnoridnyh za mehanichnymy harakterystykamy, *Fiz.-him. mehanika mater*, No. 6, 39 – 44.
2. **Andrejkiv O.E., Lischyncka M.V.** (1999), Rivnjanja rostu vtomnyh trishynh u neodnoridnyh plastynah, *Fiz.-him. mehanika mate*, No. 3, 53 – 58.
3. **Andrejkiv O.E., Rudavsky D.V.** (2004), Rozrahunkova model zarodzhenja vtomnyh trishchyn bilja navodnenogo vyrizu, *Fiz.-him. mehanika mater*, No. 5, 63 – 65.
4. **Andrejkiv O.E., Kit M. B.** (2006), Vyznachenia periodu rostu trishchyny pry ih dvochastotnomu navantazheni, *Mashynoznavstvo*, No. 2, 3 – 7.
5. **Bezimjany U. H., Halanenko D. V.** (2007), *Akusto-emisionny control v procese bysokochastotnyh ispytanij*, Konsonans, Kiev, http://www.hydromech.kiev.ua/rus/WWW-CONS/cons2007r.html
6. **Drobot U.B., Lazarev A.M.** (1987), *Nerazrushajushiy kontrol ustalostnyh treshin akustiko-emisionnym metodom*, Izd-vo standartov, 128.
7. **Gerberich W. W., Hartbower C**. (1965), *Characterization of Fatigue-Crack Growth by Stress-Wave Emission*, Aerojet-General Corporation, Sacramento, California.
8. **Gerberich W. W., Hartbower C. E.** (1966), *Feasibility Study for Measuring Fatigue-Crack Growth Rate in Welded HY-80 Steel Using Stress-Wave Emission*, Final Report of Contact N600 (167) – Sacramento, California.
9. **Harris D. O.** (1972), *Detection of Fatigue Crack Growth in a Sling Assembly by Use of Acoustic Emission Monitoring of a Periodic Proof Test*, Technical Report DC-72-3 (addition 2), Dunegan Corporation, Livermore, California.
10. **Harris D. O., Dunegan H.L**. (1974), Continuous Monitoring of Fatigue Crack Growth by Acoustic Emission Techniques, *Exper. Mech*. 17, 71–81.
11. **Hreshnikov V.A., Drobot U.B.** (1976), Akusticheskaja emisia, *Izd-vo standartov*, 272.
12. **Lindley T.C., Palmer J.C., Richards C.E**. (1978), Acoustic emission monitoring of fatigue crack growth, *Mater. Sci. Eng*., 32, No. 1, 1–15.
13. **Mitchell J.R., Egle D. M.** (1977), Acoustic emission monitoring of Fatigue Crack Propagation, Summary of paper: *ASNT Spring Conference*, Phoenix, Arizona.
14. **Mitchell J.R., Egle D. M., Appl F. J.** (1972), *Detecting Fatigue Cracks with Acoustic Emission, University of Oklahoma, school of Aerospace*, Mechanical and Nuclear Engineering, Norman, Oklahoma.
15. **Morton T.M., Smith S., Harrington R.M.** (1974), Effect of loading variables on the acoustic emission of Fatigue-Crack growth, *Exper. Stress Analysis*, 31, No. 1, 208–213.
16. **Nagornyh S.N., Sarafanov H. F.** (1990), Izluchenie AE rasprostranjajushejsa treshinoj pri ustalosti, *Nauchano-tehnicheskaja konferencia "Nerazrushajushije metody i svoistva kontrolja"*, Sverdlovsk, No. 1, 161 –162.
17. **Pavelko V., Ozolinsh E.** (2002), *Detection of Fatigue Crack by method of an Acoustic Emission*, Riga, http://www.tsi.lv/
18. **Penkin A.H., Terentev V.F**. (2006), *Akustiko-emisionyy metod kontrolja procesov plasticheskoj deformacii i razrushenia metalicheskih materialov*, ZAO SDS, Moskva, http://www.sds.ru/method.html
19. **Pollock A.A. (1989)** *Metals handbook, – ASM International*, 17, 278–294.
20. **Shata M., Terlecka Z.O.** (1999), Energetychny pidhid u mehanici vtomnogo poshyrenia mikrotrishyny, *Mehanika ruinuvania I micnist konstrukci*, T 2, Lviv: Kamenjar. 141 – 148.
21. **Skalsky V.R., Koval P.M**. (2005*), Akustychna emisia pid chas rujnuvannja matarialiv, vyrobiv i konstrukcij, Metodolohichni aspekty vidboru ta obrobky informacii*, Lviv: Spolom, – 396.
22. **Shyrjajev A.M., KamyshovA.A.** (2002), *Akusticheskaja emissia pri roste treshchin v staliah, Shestaja nauchnaja konferencia po radiofizike, Nizhnij Novgorod*, http://www.rf.unn.ru/rus/sci/books/acoust02/index.html
23. **Tensi H.M.** (2004), The Kaiser effect and its Scientific Background, *26th European Conference on Acoustic Emission Testing, Berlin*, http://www.ndt.net/article/ewgae2004 /html/htmltxt/l00tensi.htm
24. **Terlecka Z.O., Kit M. B.** (2004), Zastosuvania energetychnogo pidhodu do ocinky zalyshkovoi dovgovichnosti tonkostinnyh elementiv z poverhnevymy trishchynamy, *Mashynoznavstvo*, No. 1, 17 – 19.