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DESTRUCTION OF COMPOSITE MATERIAL BY SHEAR LOAD AND FORMATION OF ACOUSTIC RADIATION

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Abstract. Some models of the formation of acoustic emission signals by the destruction of composite material by shear load were examined. We have formulated a mathematical description of the quantity of elements that remains in the process of composite destruction and mathematical description of acoustic emission signals. The regularity of changes in acoustic emission signals for a simple model of composite destruction and for a model that takes into account the process of the destruction of the elements of composite material was shown.

Keywords: model, acoustic emission, stress, strength, shear failure, loading, signal, fracture, composite material, fibre.

1. Introduction

Composite materials are widely used in aviation and space equipment; motor, railway and water transport; and other types of machinery because of the number of advantages in composite materials. They have rather high physical-mechanical characteristics, are resistant to the influences of corrosive environments, temperature, etc. The creation and use of composite materials has led to a wide range of research connected with their destruction, control, and diagnostic methods.

For research into the destruction of composite materials, we use the conception in which the material is presented as a fibre bundle model (FBM) (Coleman 1958; Moreno *et al.* 1999; Kun *et al.* 2007; Kun, Herrmann 2000; Newman, Phoenix 2001). In such a model, it is supposed that the loss of the bearing capacity of composite material appears to be a consequence of the destruction of its fibres. And the destruction of composite material is considered to be the process of the consecutive destruction of its fibres or elements. Such assumptions are valid in the following cases. First, the matrix is flexible and less durable than the filler (fibre). Then the destruction of the matrix does not cause loss of bearing capacity of composite material; the filler stands the load. Second, the matrix is more durable than the filler. Then in case of elastic deformation, destruction starts from the fracture of the filler (formation of micro-cracks). Gradual accumulation of fractures (micro-cracks) causes destruction of the composite material. That is why we do not examine the influence of the characteristics of the matrix or the surface of matrix-filler section in the process of composite destruction.

Most theoretical and experimental research is devoted to the destruction of composite material under the conditions of uniaxial tension (Turcotte *et al.* 2003; Shcherbakov 2002; Guarino *et al.* 1998; Guarino, Garcimartin 1999; Johanson, Sornette 2000). Research allowed analytic expressions to be obtained for the number of fibres that remain in the evolution of the destruction of the composite material. We have also analysed the acoustic radiation that is built in the form of acoustic emissions (AE) accumulating energy speed changes. The correlations that are obtained characterise the processes of destruction and acoustic radiation only in the approach to the full destruction of the material. At the moment of the destruction of the composite material, all research functions rupture. Such ambiguity does not allow a mathematic expression to be obtained for the description of the AE signal formed.

In articles articles (Filonenko *et al.* 2009a, 2010) models of AE signals by thermo-activated and predominantly mechanical destruction of composite material by a stretching load were developed. Models are formed on the FBM conception and the kinetics of the destruction process. The kinetic approach was also used in works (Babak *et al.* 2005, 2006; Filonenko *et al.* 2008). The models that were developed (Filonenko *et al.* 2009a, 2010) allow changes in the regularities of acoustic radiation characteristics under the influence of different factors (Filonenko *et al.* 2009b, 2011; Filonenko 2011) to be investigated, conforming to the results of experimental research.

At the same time, one more interesting point is analysis of the destruction of composite material by shear load. Such loads appear in products that work in conditions of cyclic and dynamic load, for example, friction units. Models for the research of processes of composite material destruction under the influence of shear loads are examined in (Raischel *et al.* 2005, 2008; Kun *et al.* 2006, 2007, 2000; Herrmann *et al.* 2009; Pradhan, Chakrabarti 2006; Kun, Nagy 2008; Kovács *et al.* 2008; Reiweger *et al.* 2009). The models are formed under definite initial conditions. So, in works (Raischel *et al.* 2005, 2008; Kun *et al.* 2006, 2007; Herrmann *et al.* 2009) it is supposed that fibres have similar sizes and are evenly distributed throughout the composite. By the apposition of shear to the composite material load, the fibres are deformed elastically and the distance between the planes of the attachment of the fibres does not change. It is considered that by such a load on the composite material, deformation and stress are equal on all fibres. Supposing that distribution of the threshold levels of bending and stretching deformation are independent, the authors of the aforementioned works obtained an expression for change in general stress on fibres in the process of their fracture in the following form

$$\sigma = \varepsilon \int_{q(\varepsilon)}^{\varepsilon_{2\max}} d\varepsilon_2 p_2(\varepsilon_2) \int_{f(\varepsilon)}^{\varepsilon_{1\max}} d\varepsilon_1 p_1(\varepsilon_1) =$$
$$\varepsilon[1 - P_2(q(\varepsilon))][1 - P_1(f(\varepsilon))], \quad (1)$$

where ε – deformation; $p_1(\varepsilon_1)$, $p_2(\varepsilon_2)$ – density of probabilities of threshold levels under stretching and bending, respectively; $P_2(q(\varepsilon))$, $P_1(f(\varepsilon))$ – functions of distribution; $f(\varepsilon)$ and $q(\varepsilon)$ – functions of fibre failure.

Expression (1) was got supposing that there are two independent ways of destruction or the 'or rule'. The 'or rule' assumes that destruction of the fibre under the influence of share load takes place when its deformation of stretching or bending reaches the definite level ε_1 or ε_2, that is the conditions of the following form are implemented:

$$\frac{f(\varepsilon)}{\varepsilon_1} \geq 1, \quad (2)$$

or

$$\frac{q(\varepsilon)}{\varepsilon_2} \geq 1. \quad (3)$$

Let us write the functions for the failure of fibres in the following form:

$$f(\varepsilon) = \varepsilon, \quad q(\varepsilon) = g\sqrt{\varepsilon}, \tag{4}$$

where g is a coefficient that depends on the geometrical sizes of the fibre and modulus of elasticity $E = 1$.

For independent even distribution of threshold levels ε_1 and ε_2 in the range of values ($\varepsilon_{1\min}$, $\varepsilon_{1\max}$) and ($\varepsilon_{2\min}$, $\varepsilon_{2\max}$), according to (Raischel *et al.* 2005), expression (1) will have the following form:

$$\sigma = \varepsilon \frac{\left(\varepsilon_{1\max} - f(\varepsilon)\right)\left(\varepsilon_{2\max} - q(\varepsilon)\right)}{\left(\varepsilon_{1\max} - \varepsilon_{1\min}\right)\left(\varepsilon_{2\max} - \varepsilon_{2\min}\right)}. \tag{5}$$

According to the accepted model, if the initial number of fibres is N_0, then the quantity of fibres N_i that remains in the process of composite destruction can be described with the help of the following expression:

$$\frac{N_i}{N_0} = \int_{q(\varepsilon)}^{\varepsilon_{2\max}} d\varepsilon_2 \int_{f(\varepsilon)}^{\varepsilon_{1\max}} d\varepsilon_1 p(\varepsilon_1, \varepsilon_2), \tag{6}$$

so that it is defined by comparison of deformation with its boundary values $f(\varepsilon) \le \varepsilon_1 \le \varepsilon_{1\max}$ and $q(\varepsilon) \le \varepsilon_2 \le \varepsilon_{2\max}$.

In case of the independent fracture of fibres in the range of deformation on the intersection of the bounds [$\varepsilon_{1\min}$, $\varepsilon_{1\max}$] and [$\varepsilon_{2\min}$, $\varepsilon_{2\max}$], expression (6) will have the following form:

$$\frac{N_i}{N_0} = \frac{\varepsilon_{1\max} - f(\varepsilon)}{\varepsilon_{1\max} - \varepsilon_{1\min}} \frac{\varepsilon_{2\max} - q(\varepsilon)}{\varepsilon_{2\max} - \varepsilon_{2\min}}. \tag{7}$$

Expressions (5) and (7) allow making calculations of stress and number of undestroyed fibres under the conditions of composite material deformation, when two processes of fibre destruction take place due to stretching and bending.

Obviously, destruction of fibres will be accompanied by acoustic radiation. AE amplitude can be calculated with the help of expression (7). Such a model will be elementary. It will allow the process of the formation of acoustic radiation to be estimated effectively and precisely, and then it can be compared with the process of the destruction of composite material fibres. We can also examine other cases of fibre destruction, for example, according to the rule of Mises or when threshold levels of destruction are described by Poisson distribution (Raischel *et al.* 2005, 2008; Kun *et al.* 2006, 2007; Herrmann *et al.* 2009). We will confine ourselves to the examination of the model of acoustic radiation for a more specific case of the 'or rule', when distribution of threshold levels of destruction are independent and even with borders (0, 1). Thus, we shall take into consideration the kinetics of the evolution of composite destruction.

2. Results of research

While examining the composite material destruction let's take into account all the conditions considered in works (Raischel *et al.* 2005, 2008; Kun *et al.* 2006, 2007; Herrmann *et al.* 2009). Let us suppose that a model of composite consists of N_0 fibres (components) of equal size, which are evenly distributed over its volume. We will consider that the matrix does not influence the process of the composite bearing capacity loss. Let us suppose that by application of shear load to the elements, they deform elastically. The distance between the planes of element fastening does not change. Providing there is such a composite material load, a bending moment and a stretching effect appear on its elements. We will consider that destruction of the elements in the model happens in consecutive order. Besides, the external load is redistributed evenly on the remaining elements, which are exposed to the same growing axial deformation. Let us assume that elements destruct when their deformation reaches a specific threshold level, so that destruction happens due to bending or stretching.

Let us suppose that deformation of composite material happens with constant speed and is described with the help of the following expression:

$$\varepsilon = \alpha t, \tag{8}$$

where α = const–speed of load.

Obviously, the destruction of composite material will be accompanied by the formation of acoustic radiation. Let us take the conditions of formation of acoustic radiation as in work (Filonenko *et al.* 2010). We will assume that destruction of each element of composite material forms a single disturbance impulse. This impulse is spread over the material in the form of a displacement impulse that has no attenuation. The type of disturbance impulse is shown in Fig. 1, where A_0 – amplitude value of single impulse of disturbance; δ – duration of impulse of disturbance. Let us consider that the duration of the impulse of disturbance δ is small and much smaller than the time of the destruction of the model of composite material.

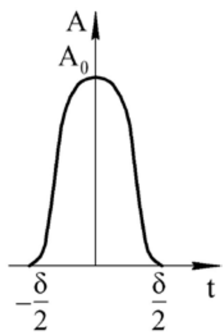


Fig. 1. Form of disturbance impulse during the destruction of composite material

Under such conditions, the resultant displacement will be determined by a number of disturbance impulses that are formed during some unit of time, and therefore it will be proportional to the speed of element destruction $D(t)$. We will define the speed of element destruction $D(t)$ in the following way:

$$D(t) = \frac{1}{N_0}\frac{dN_P(t)}{dt} = -\frac{1}{N_0}\frac{dN_i(t)}{dt}, \tag{9}$$

where N_0 – initial number of elements; N_P – number of destroyed elements; N_i – number of remaining elements. In expression (9), we adopted the following sign:

$N_P = N_0 - N_i$.

According to the adopted conditions, destruction of each element takes place when there is some boundary value of axial deformation. That is why the amplitude of the disturbance impulse will depend on its size. The bigger the boundary value of axial deformation is, the bigger the amplitude of disturbance impulse will be, so that $A_0(t) \sim \varepsilon(t)$ or $A_0(t) = \beta\varepsilon(t)$, where β – coefficient of proportionality. In general for the disturbance impulse, it is possible to write the following expression:

$$A(t,\tau) = A_0(t)a(\tau), \tag{10}$$

where $a(\tau)$ – function that defines the form of the excitation impulse.

Let us consider that function $a(\tau)$ is equal for all disturbance impulses and has a single amplitude. Total displacement $U(t)$, which is formed during time interval ($t-\delta/2$, $t+\delta/2$), will be defined by the following integral:

$$U(t) = \int_{t-\frac{\delta}{2}}^{t+\frac{\delta}{2}} A_0(t)a(\tau)D(t+\tau)d\tau. \tag{11}$$

We made the assumption that the duration of disturbance δ is much shorter than the time of the destruction process of all N_0 elements of the composite material. That is why we can neglect changes in values $D(t)$ and $A_0(t)$ during the time interval ($t-\delta/2$, $t+\delta/2$). Then expression (11) can be written in the following way:

$$U(t) = D(t)A_0(t)\int_{t-\frac{\delta}{2}}^{t+\frac{\delta}{2}} a(\tau)d\tau. \tag{12}$$

Let us accept the sign $\delta_S = \int_{t-\frac{\delta}{2}}^{t+\frac{\delta}{2}} a(\tau)d\tau$. The numerical value δ_S is defined by the form of a single disturbance impulse and has dimension of time. Taking into account (8), expression (12) can be written in the following way:

$$U(t) = u_0\alpha t D(t), \tag{13}$$

where $u_0 = \beta\delta_S$ – constant value.

It is important to note that the use of a broadband sensor to register the AE signal on its output will repeat the disturbance impulse, which is described by expression (13). That is why we will talk about the AE signal.

For the calculation of the AE signal, it is necessary to define the speed of element destruction $D(t)$. Let us examine two cases while making calculations.

The first case is when threshold levels ε_1 and ε_2 are independent and have even distributions in the range of ($\varepsilon_{1\min}$, $\varepsilon_{1\max}$) and ($\varepsilon_{2\min}$, $\varepsilon_{2\max}$) values. In this case, stress on the elements and the quantity of the remaining elements are described with the help of the expressions (5) and (7), respectively.

According to the accepted conditions, destruction of the elements takes place due to bending and stretching, and therefore it starts at the same period of time when $t_{1\min} = t_{2\min}$. Parameters $t_{i\min}, t_{i\max}$ are determined from an expression in the following form:

$$t_{i\min} = \frac{\varepsilon_{i\min}}{\alpha},\quad t_{i\max} = \frac{\varepsilon_{i\max}}{\alpha}.$$

Taking into account (4) (accepted g = 1) and (8), let us rewrite expressions (5) and (7) in the following form:

$$\sigma = \alpha t \frac{\varepsilon_{1\max} - \alpha t}{\varepsilon_{1\max} - \varepsilon_{1\min}} \frac{\sqrt{\varepsilon_{2\max}} - \sqrt{\alpha t}}{\sqrt{\varepsilon_{2\max}} - \sqrt{\varepsilon_{2\min}}}, \tag{14}$$

$$\frac{N_i}{N_0} = \frac{\varepsilon_{1\max} - \alpha t}{\varepsilon_{1\max} - \varepsilon_{1\min}} \frac{\sqrt{\varepsilon_{2\max}} - \sqrt{\alpha t}}{\sqrt{\varepsilon_{2\max}} - \sqrt{\varepsilon_{2\min}}}. \tag{15}$$

Then, according to (13), the time dependence of the AE signal in the process of the destruction of composite elements will have the following form:

$$U(t) = \frac{1}{2}u_0\alpha \frac{t_{1\max}\sqrt{t} + 2t\sqrt{t_{2\max}} - 3t\sqrt{t}}{(t_{1\max} - t_{\min})(\sqrt{t_{2\max}} - \sqrt{t_{\min}})}, \tag{16}$$

where $t_{1\min} = t_{2\min} = t_{\min}$.

The expression (16) is accomplished from the moment $t = t_{\min}$ at time interval ($t_{\min}$, $t_{2\min}$) if $t_{2\min} < t_{1\min}$ or at time interval ($t_{\min}$, $t_{1\min}$) if $t_{1\min} < t_{2\min}$.

In Fig. 2 the results of modelling regularities in stress changes, quantity of (non-destroyed) elements that were left, and AE signal according to (14), (15) and (16) are given in relative units. In the plots (Fig. 2), all the parameters of expressions (14), (15) and (16) are brought to dimensionless quantities. For curve 1 (Fig. 2), the parameters that are included in expressions (14), (15) and (16) had the following values: $\tilde{\alpha}$ =100, $\tilde{\varepsilon}_{1\min}$ = 5, $\tilde{\varepsilon}_{1\max}$ = 30, $\tilde{\varepsilon}_{2\min}$ = 5, $\tilde{\varepsilon}_{2\max}$ = 20, $\tilde{t}_{1\min}$ = 0.05, $\tilde{t}_{1\max}$ = 0.3, $\tilde{t}_{2\min}$ = 0.05, and $\tilde{t}_{2\max}$ = 0.2. Time was calculated according to (8). For curve 2 (Fig. 2), the range of the top boundary values ε_1 and ε_2 was expanded: $\tilde{\alpha}$ = 100, $\tilde{\varepsilon}_{1\min}$ = 5, $\tilde{\varepsilon}_{1\max}$ = 40, $\tilde{\varepsilon}_{2\min}$ = 5, $\tilde{\varepsilon}_{2\max}$ = 30, $\tilde{t}_{1\min}$ = 0.05, $\tilde{t}_{1\max}$ = 0.4, $\tilde{t}_{2\min}$ = 0.05, and $\tilde{t}_{2\max}$ = 0.3.

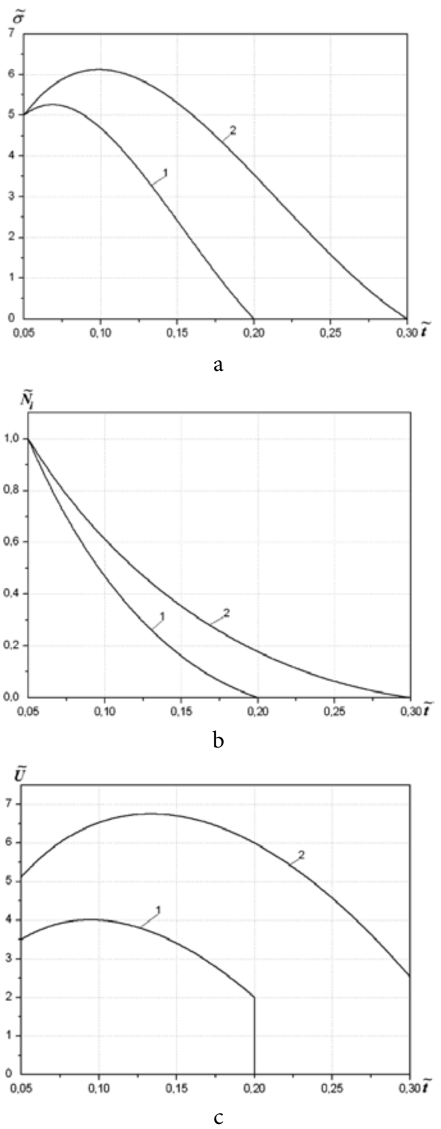


Fig. 2. Dependences of stress changes (a), numbers of non-destroyed elements (b), and AE signal (c) in relative units in case of destruction of composite material by shear load. Deformation speed $\tilde{\alpha} = 100$. For curve 1: $\tilde{\varepsilon}_{1\min} = 5$, $\tilde{\varepsilon}_{1\max} = 30$, $\tilde{\varepsilon}_{2\min} = 5$, $\tilde{\varepsilon}_{2\max} = 20$, $\tilde{t}_{1\min} = 0.05$, $\tilde{t}_{1\max} = 0.3$, $\tilde{t}_{2\min} = 0.05$, and $\tilde{t}_{2\max} = 0.2$. For curve 2: $\tilde{\varepsilon}_{1\min} = 5$, $\tilde{\varepsilon}_{1\max} = 40$, $\tilde{\varepsilon}_{2\min} = 5$, $\tilde{\varepsilon}_{2\max} = 30$, $\tilde{t}_{1\min} = 0.05$, $\tilde{t}_{1\max} = 0.4$, $\tilde{t}_{2\min} = 0.05$, and $\tilde{t}_{2\max} = 0.3$

In Fig. 2a, it can be seen that composite material destruction is characterised by the appearance of non-linearity depending on the changes in stress. The changing dependence of non-destroyed elements continuously decreases (Fig. 2b). The destruction is accompanied by acoustic emission radiation (Fig. 2c). Obviously, the definition of the deflection from linearity of $\sigma(t)$ is a difficult task, especially under the conditions of an experiment. But the AE signal appears at the moment when element destruction starts due to either stretching or bending. This means that AE is registered independently of how the destruction happens; hence AE is an indicator of critical stress on the elements of the composite material.

The results of modelling (Fig. 2) also show that, if there is constant increase in the speed of composite load and if the upper range of boundary values ε_1 and ε_2 is expanded, there is an increase in maximal stress value, time of the destruction process, and maximal amplitude of AE signal. This corresponds to the existing concepts of destruction mechanics and the accepted assumption about the dependence of the amplitude of the disturbance impulse on boundary deformation value.

The description of all these processes is simple. As research has shown, real AE signals have more difficult forms. They differ from the signals shown in Fig. 2. This is because of the more complicated redistribution of stress in composite material and because the kinetics of the process of the destruction of composite elements were not taken into account when describing the acoustic radiation.

Let us analyse the second case of the destruction of composite material, when threshold levels ε_1 and ε_2 have an independent, even distribution with borders (0, 1). We will take the same starting conditions for building this model of composite destruction.

In light of the functions of failures $f(\varepsilon)$ and $q(\varepsilon)$, expression (4), expression (5) in article (Raischel *et al.* 2005) is modified give the following expression:

$$\sigma(\varepsilon) = \varepsilon(1-\varepsilon)(1-g\sqrt{\varepsilon}), \tag{17}$$

where g–a coefficient that depends on the geometrical sizes of the fibre (area of cross-section and length).

Expression (17) describes the dependence of equivalent stress changes on the fibres during the process of composite destruction. The continuity of deformation ε over time is a condition of existence (17).

Let us assume that the deformation of a sample of the composite happens according to (8). Then expression (17) will be written in the following form:

$$\sigma(t) = \alpha t(1-\alpha t)(1-g\sqrt{\alpha t}). \tag{18}$$

The application of axial deformation allows using the general expression for the change in the speed of the quantity of the residual fibres over time during the process of destruction, which was examined in articles (Turcotte *et al.* 2003; Shcherbakov 2002). This expression is also used in work (Filonenko *et al.* 2010) in a type of kinetic equation of the destruction of composite material.

$$\frac{dN}{dt} = -\upsilon(\sigma)N, \tag{19}$$

where $N = N_0 - N_Đ(t)$ – quantity of the residual elements; N_0 – initial quantity of elements; $N_Đ(t)$ – quantity of destroyed elements; $\upsilon(\sigma)$ – speed of the destruction process, which depends on stress $\sigma(t)$.

According to kinetic theory (Malamedov 1970), starting from a moment in time t_0 that corresponds to the beginning of the destruction, the speed of the developing process increases according to exponential law, that is

$$\upsilon = \upsilon_0 \, e^{r[\sigma(t)-\sigma(t_0)]}, \quad (20)$$

where υ_0, r – constants that depend on the physic-mechanical characteristics of the composite material; $\sigma(t)$ – change in stress over time; $\sigma(t_0)$ – threshold stress that corresponds to the start t_0 of destruction.

Expression (20) identifies the avalanche-like character of the process of the destruction of composite material.

Taking into account (18) and (20), expression (19) will have the following form:

$$\frac{dN}{N} = -\upsilon_0 \text{ x } \text{x}e^{r[\alpha t(1-\alpha t)(1-g\sqrt{\alpha t})-\alpha t_0(1-\alpha t_0)(1-g\sqrt{\alpha t_0})]}dt \quad (21)$$

Before the moment in time $t = t_0$, the value $N_D(t)$ is zero, that is $N_D(t_0) = 0$. Accounting for this and having done integration (21), we will get an expression for the quantity of residual elements over time during the evolution of their destruction process.

$$N(t) = N_0 \text{x} \; \text{x}e^{-\upsilon_0 \int_{t_0}^{t} e^{r[\alpha t(1-\alpha t)(1-g\sqrt{\alpha t})-\alpha t_0(1-\alpha t_0)(1-g\sqrt{\alpha t_0})]}dt}. \quad (22)$$

Solution (12) in symbolic form is impossible. Consequently, hereinafter we will make the analysis of regularities in the changes in the quantity of residual elements over time during the evolution of the destruction process using numerical solution (22).

Undoubtedly, the process of composite destruction will be accompanied by the formation of an AE signal. Let us take the same conditions for the formation of the AE signal as it is given above. In general the disturbance impulse will then be described with the help of expression (10). Its amplitude $A_0(t)$ will be determined by destruction stress, so that $A_0(t) = \vartheta\sigma(t)$, where ϑ – coefficient of proportionality. In light of (18), $A_0(t)$ can be written in the following form:

$$A_0(t) = \vartheta\sigma(t) = \vartheta[\alpha t(1-\alpha t)(1-g\sqrt{\alpha t}) - -\alpha t_0(1-\alpha t_0)(1-g\sqrt{\alpha t_0})] \quad (23)$$

As earlier, let us consider that function $a(\tau)$ is equal for all impulses of disturbance and have a unit amplitude.

Total displacement $U(t)$ that is formed during the time interval ($t-\delta/2$, $t+\delta/2$) will be defined by integral (12). Having taken the conditions examined above and having included the sign $\delta_S = \int_{t-\frac{\delta}{2}}^{t+\frac{\delta}{2}} a(\tau)d\tau$, we receive expression (12) with the following form:

$$U(t) = \delta_S D(t) A_0(t), \quad (24)$$

where $D(t)$ = dN/dt - speed of the change in residual elements over time.

Having made differentiation (22), we get an expression for the speed of the change in the remained elements.

$$D(t) = \left|\frac{dN(t)}{dt}\right| = N_0\upsilon_0 \text{x} \; \text{x}e^{r[\alpha t(1-\alpha t)(1-g\sqrt{\alpha t})-\alpha t_0(1-\alpha t_0)(1-g\sqrt{\alpha t_0})]} \text{x} \; \text{x } e^{-\upsilon_0 \int_{t_0}^{t} e^{r[\alpha t(1-\alpha t)(1-g\sqrt{\alpha t})-\alpha t_0(1-\alpha t_0)(1-g\sqrt{\alpha t_0})]}dt}. \quad (25)$$

In light of (23) and (25), expression (24) will then have the following form:

$$U(t) = U_0\upsilon_0[\alpha t(1-\alpha t)(1-g(\alpha t)^{\frac{1}{2}}) - -\alpha t_0(1-\alpha t_0)(1-g(\alpha t_0)^{\frac{1}{2}})]\text{x} \; \text{õ } e^{r[\alpha t(1-\alpha t)(1-g\sqrt{\alpha t})-\alpha t_0(1-\alpha t_0)(1-g\sqrt{\alpha t_0})]}\text{x} \; \text{x } e^{-\upsilon_0 \int_{t_0}^{t} e^{r[\alpha t(1-\alpha t)(1-g\sqrt{\alpha t})-\alpha t_0(1-\alpha t_0)(1-g\sqrt{\alpha t_0})]}dt}. \quad (26)$$

where $U_0 = N_0\,\vartheta\delta_S$ –maximal possible displace-ment in case of instantaneous destruction of a pattern of the composite material consisting of N_0 elements.

Solution (26) in symbolic form is impossible. Hence, hereinafter we, using numerical solution (26), will analyse the regularities in the amplitude of AE signals as they change over time during the evolution of the destruction process.

From expressions (22) and (26), it can be seen that, if the destruction process is taking place,

the quantity of the remaining elements and the characteristics of the AE signal depend on the quantity of initial elements, speed of the load, physical and mechanical characteristics of the composite material, and geometrical sizes of its elements. Let us model $\sigma(t)$, $N(t)$ and $U(t)$ depending on α with set values of physical and mechanical characteristics of the composite material and constant N_0 value.

In Fig. 3, dependences of stress changing over time are shown, according to (18), in relative units for different values of $\tilde{\alpha}$. By calculation $\tilde{\sigma}(\tilde{t})$ time is normed with the deformation time, which has a constant value ($\tilde{t}_{max}$). Parameter $\tilde{\alpha}$ is modified to a dimensionless quantity. Its values change from 50 to 150. The value of coefficient $\tilde{g}$ is taken to equal $\tilde{g}$ = 0.1. An increase in $\tilde{\alpha}$ means an increase in deformation speed.

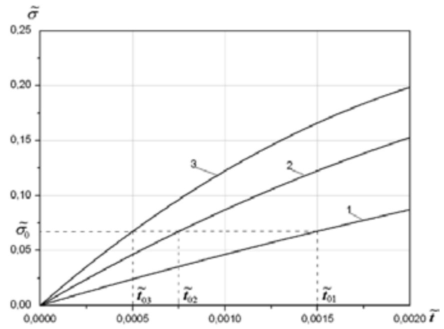


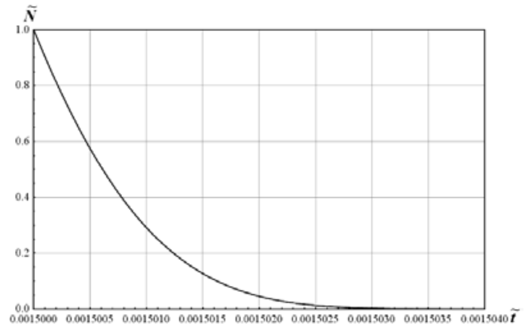
Fig. 3. Dependence of stress changing over time, according to (18), for different values $\tilde{\alpha}$: 1 – $\tilde{\alpha}_1$ = 50; 2 – $\tilde{\alpha}_2$ = 100; 3 – $\tilde{\alpha}_3$ = 150. The value of parameter $\tilde{g}$ is $\tilde{g}$ = 0.1

Fig. 3 demonstrates that the increase in $\tilde{\alpha}$ leads to a rise in the slope and causes changes in stress over time. At the same time, calculations show that the maximum value of stress remains the same. Depending on the load speed, it will take different periods of time to achieve a value of one and the same level of stress. For example, stress $\tilde{\sigma}_0$, which corresponds to the start of the destruction of the composite material, is reached at different periods of time (Fig. 3), and therefore for $\tilde{\alpha}_1 < \tilde{\alpha}_2 < \tilde{\alpha}_3$ condition $\tilde{t}_{01} > \tilde{t}_{02} > \tilde{t}_{03}$ is performed.

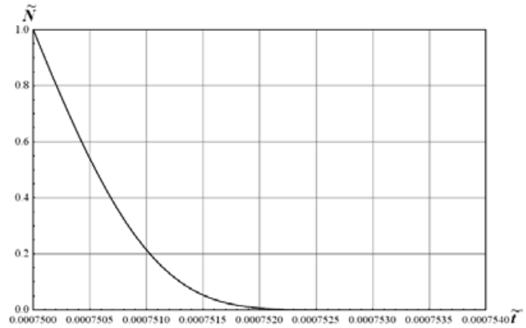
Let us model $N(t)$ and $U(t)$ according to (22) and (26) under the following conditions. Value $\tilde{\alpha}$ is 50, 100 and 150. Threshold stress of destruction (in relative units) for all values $\tilde{\alpha}$ is $\tilde{\sigma}_0$ = 0.06747508737865396. Values of destruction start time for speeds of deformation $\tilde{\alpha}_1$ = 50, $\tilde{\alpha}_2$ = 100 and $\tilde{\alpha}_3$ = 150 (Fig. 3) are $\tilde{t}_0$ = 0.0015, $\tilde{t}_{01}$ = 0.0015, $\tilde{t}_{02}$ = 0.00075, and $\tilde{t}_{03}$ = 0.0005. Let us assume that the value of parameter $\tilde{g}$ is equal to $\tilde{g}$ = 0.1. The values of quantities υ_0 and r, included in (22) and (26), were chosen due to the following reasons. Parameter r is connected with the sensitivity of the material to stress and characterises the dispersibility of its strength properties. For material with small dispersibility of characteristics, $r >> 1$. Parameter υ_0 characterises the strength of the lattice and up to a degree of the value corresponds to $1/\tau_0$, where τ_0 – period of oscillations of the atomic lattice, so that $\upsilon_0 >> 1$.

We will assume that the values of the given parameters are equal to: $\tilde{\upsilon}_0 = 1000000$ and $\tilde{r}$ = 10000. All the parameters included in (22) and (26) will be modified to dimensionless quantities by modelling.

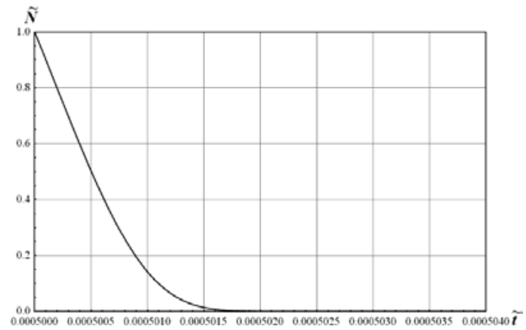
The dependences of changes in the quantity of remaining elements $\tilde{N}(t) = N(t)/N_0$ for the accepted conditions in relative units are shown in Fig. 4. Dependences $\tilde{N}(t)$ persistently decrease. Together with the increase in $\tilde{\alpha}$, we can see a growth in the decrease in received dependences, displacement of destruction start $\tilde{t}_0$ to lower values, and increase in the duration of the destruction process (Fig. 4). The starting time of destruction decreases in proportion to the increase in composite material load speed.



a



b



c

Fig. 4. Dependences of change in the quantity of elements remaining over time according to (22), in relative units during destruction of composite material by shear load. Values $\tilde{\alpha}$: *a* – $\tilde{\alpha}_1$ = 50, *b* – $\tilde{\alpha}_2$ = 100, *c* – $\tilde{\alpha}_3$ = 150. $\tilde{\upsilon}_0 = 1000000$, $\tilde{r}$ = 10000, $\tilde{\sigma}_0$ = 0.06747508737865396, $\tilde{g}$ = 0.1. Start time of destruction: *a* – $\tilde{t}_{01}$ = 0.0015, *b* – $\tilde{t}_{02}$ = 0.00075, *c* – $\tilde{t}_{03}$ = 0.0005

Dependences of changes in the amplitude of the AE signals for the accepted conditions in the form of graphics $\tilde{U}(t) = U(t)/U_o$ in relative units are shown in Fig. 5. From this it can be seen that AE signals have a fast increase in amplitude on the leading edge and relaxed decrease in amplitude on the trailing edge.

With the increasing in $\tilde{\alpha}$, we can observe displacement of the start time of AE signal formation, which corresponds to the moment the destruction of the composite material $\tilde{t}_0$ starts. Under such conditions, the amplitude of AE signals increases and compression in time takes place; AE duration therefore decreases (Fig. 5). Besides, an increase in deformation speed leads to the transformation of the form of the AE signal. Its form gradually approaches the signal of a triangle waveform.

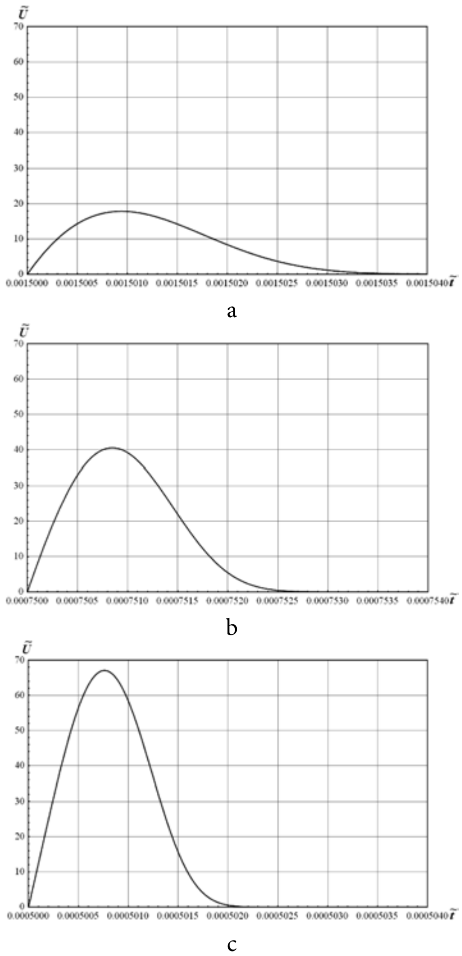


Fig. 5. Dependence of change in amplitude of AE signals over time according to (26) in relative units during the destruction of composite material by shear load. Values $\tilde{\alpha}$: *a* – $\tilde{\alpha}_1 = 50$; *b* – $\tilde{\alpha}_2 = 100$; *c* – $\tilde{\alpha}_3 = 150$. $\tilde{\upsilon}_0 = 1000000$, $\tilde{r} = 10000$, $\tilde{\sigma}_0 = 0.06747508737865396$, $\tilde{g} = 0.1$. Start time of destruction: *a*– $\tilde{t}_{01} = 0.0015$; *b*– $\tilde{t}_{02} = 0.00075$; *c*– $\tilde{t}_{03} = 0.0005$

Regularities of changes in the curves of remaining elements over time and the signals being formed are caused by the fact that together with the increase in $\tilde{\alpha}$, in consideration of the kinetic process, the speed of the destruction of the elements of composite material rises, so that the quantity of elements that are destroyed per unit of time increases. This change in the destruction process causes a decrease in its time and an increase in its intensity. In regards to the destruction process, the duration of the AE signals being formed is much shorter than the duration of the AE signals that were received for a simple model of composite destruction by shear load.

3. Conclusions

We made a very simple description of the formation of AE signals during the destruction of composite material by shear load. On the qualitative level, it has been shown that it is practically impossible to define the beginning of the composite destruction process by shear load according to the dependence of changes in axial stress over time. At the same time, as research has showed, AE signals appear directly at the starting point of the destruction of composite material. Registration of AE signals during composite material load can be used to determine the point at which maximum acceptable load is reached.

Actual AE signals differ from modelled ones, however. This happens because in a simple model gradual, rather slow destruction of composite material was assumed.

We described acoustic radiation while taking into account the more difficult character of the redistribution of stress during composite destruction by shear load. While describing acoustic radiation, we made an accounting of the kinetic aspect of the destruction process. It is shown that the change in the curve of the remaining elements over time continually declines. The continuity of the destruction process is accompanied by the formation of a continuous AE signal. The AE signal is characterised by accelerating increase leading edge of the amplitude and gradual fall on the trailing edge. It is shown that an increase in the speed of the deformation of composite material causes a reduction in the amount of time the destruction process takes place because of the increasing speed of its development. This process of composite material destruction is accompanied by a steeper drop in the curves of the remaining elements. A change in the characteristics and shape of the AE signal takes place. An increase in amplitude, decrease in duration, and transformation of the form of the AE signal into a triangle waveform can be observed. All results received conform to existing conceptions concerning the influence of deformation speed on the process of the destruction of materials, including composite materials.

This theoretical research is the basis for creating a model of resultant AE signal during dynamic loading of products. The model obtained in this article will be verified in laboratory tests involving the diagnosis of friction units.

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