GENERATION OF ACOUSTIC EMISSION PULSES DURING COHERENT FRACTURE

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ABSTRACT

The deformation and fracture of solids are accompanied by acoustic emission. Plastic deformation and ductile fracture are characterized by stochastic unresolvable acoustic pulses - continuous emission. The brittle fracture is accompanied by the radiation of acoustic-emission pulses or burst emission. In this paper developed the model of generation of acoustic emission pulse.

KEYWARDS
acoustic emission, fracture, brittle, coherent, pulse

Consider an idealized crystal structure (cubic, for example) represented at Fig.1. It is loaded mechanically along the vertical Z axis. The distance between atoms increases from "a" ("a" - the lattice parameter) to r_m. When the distance between two atoms exceeds the critical value r_m, the atomic bond is broken. Under the action of attraction to other atoms in the lattice, the given pair of atoms moves apart dynamically. Other atomic bonds existing on the continuation of the given bond along the Z axis relax,

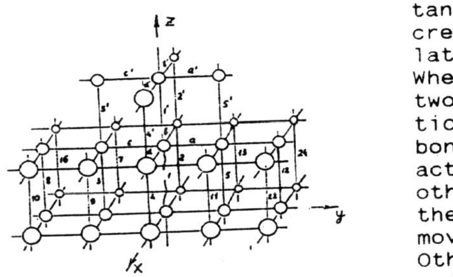

Fig.1. Model of crystal lattice of a solid

and stored elastic energy is released in the amount equal to the work done in moving the atom from r_m to a. The relaxation energy of a single bond is $E = \int_{r_m}^{a} f dr$. The rupture of a single atomic bond represents a quantum of fracture (Novozhilov, 1969) and serves as a trigger mechanism for generation of an acoustic radiation flux associated with relaxation of the atomic bonds in a certain volume of the solid. The acoustic flux, or acoustic emission, characterizes the fracture process in the solid, and a single acoustic emission pulse can be attributed to each elementary event of relaxation of a single bond.

The relaxing volume of the solid is bounded, on the one hand, by the surface (plane) in which the bonds rupture and, on the other hand, by a surface or domain whose dimensions are determined by the St.Venant principle (Berdichevskii,1974). According to the principle, the stress field in a zone of inhomogeneity and the perturbation created by that inhomogeneity extend to distances commensurate with the size of the inhomogeneity. In our case, the dimensions of the inhomogeneity are determined by the dimensions of the bond-rupture domain.

The perturbation from the first ruptured bond {1} is transmitted by transverse motion (relative to the *xy* plane) to the surrounding adjacent bonds {2,3,4,5} causing them to rupture. The atomic bonds through which the perturbations are transmitted in the form of transverse displacements of the atoms form a square grid (Fig.2) in the *xy* plane in the case of a cubic lattice. At each subsequent time, the perturbation responsible for bond rupture is transmitted to the nearest neighbor bonds oriented along the z axis. These times are separated in the given simplified model by the time required for transverse vibrations to propagate from the ruptured bond to the nearest-neigbor bonds.

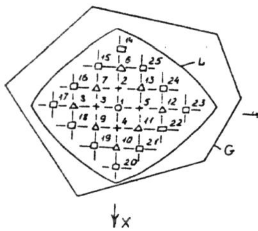

Fig.2.Bond-rupture sequance, step by step, from ∘ to □.

The bond-rupture front propagates in the *xy* plane and in the case of a cubic lattice has the shape of a square, whose sides and area increase in the course of propagation of the rupture (fracture) process. Each side of the square grows in each successive step by one atomic bond and, accordingly, the perimeter increases by four bonds. The growth factor for an arbitrary lattice is equal to the coordination number *k* in stereographic projection onto the *xy* plane.

In this case, the equation for the increment of the number of ruptured bonds has the simple form:

$$\frac{d(\Delta N)}{dt} = K \qquad (1)$$

Here ΔN has the significance of the increment of the number of ruptured bonds in the fracture plane; it is related to the increment of the number of ruptured bonds per unit time according to the expression:

$$\Delta N = \frac{dN}{d\tau} = \frac{1}{v}\frac{dN}{dt} \qquad (2)$$

where v is the rate of propagation of ruptures (dr=vdt). Assuming that this rate is constant and equal to unity, we obtain from (1) the time dependence of the increment of the number of ruptured bonds:

$$\Delta N = \kappa t \qquad (3)$$

and the number of elementary acoustic-emission pulses, which is determined by the integral in Eq.(2), is

$$N = \frac{\kappa t^2}{2} \qquad (4)$$

The above-described bond-rupture proces continues until the coherence of the static extension and the dynamic action is disrupted. The coherent state corresponds to the action of a dynamic perturbation along the line of extension promoting bond rupture. When the disruption of coherence attains a definite degree, the bond is not ruptured.

The disruption of coherence can be associated with a defect in the crystal structure(inclusion, vacancy, dislocation, grain boundary, etc.) or with some kind of dynamic process. The rupture of bonds in an ideal lattice propagates until it completely divides the solid. The rupture front propagates rapidly, with the transverse-wave velocity in the given state of the material (unless crack branching takes place); the spreading of the edges of a crack, which completes the fracture process, propagates with the surface-wave velocity. Such "rapid" fracture, which leaves the structure of the material in the zones adjacent to the fracture surface unaltered, is considered to be brittle fracture.

When the structure is disrupted, the rupture of bonds stops, and only the part of the solid bonded by the inhomoheneity of the structure or the stress field is involved in brittle fracture. It is simplest to portray the cessation of the bond-rupture process by assuming that it terminates when the rupture front, e.g., reaches the grain boundaries.

For a square grid and a grain bounded by a square we have two extreme cases of the rupture front encountering the boundaries. In the case in which the rupture front is parrallel to the boundary, the bound-rupture process stops "instantaneously". In the case of oblique "incidence" of the rupture front on the boundary, the namber of ruptures decreases linearly. Figure 3 shows curves of the number of ruptured bonds for a square crystallographic grid and for the initiation of fracture at the center of the square. Curve 1 corresponds to the case of fracture fronts parallel to the grain boundaries, and curve 2 to oblique "incidence" of the rupture fronts on the boundary with a 45o angle of disorientation.

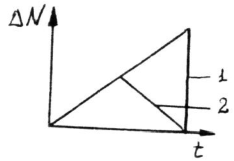

Fig.3. Curves of the number of ruptured bonds

The start of fracture, i.e., the position of the first ruptured bond, is distributed uniformly throughout the volume in a homogeneous material and is determined by thermal fluctuation processes. For a real material characterised by appreciable inhomogeneity, however, the start of fracture is more likely situated near an inhomogeneity. For a random position of the start of fracture and for a grain of random shape and random orientation of its boundaries, we obtain a smooth decrease in the number of ruptured bonds. Numerical calculation for grains with the shape of boundaries taken from metallographic studies have yielded the average curve shown in Fig.4 for the variation of the number of ruptured bonds.

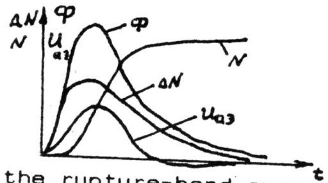

Fig.4. Shape of the rupture-bond curves and the AE signal.

The calculated average curve can be approximated by the expression (5):

$$\Delta N = K t e^{-\delta t} \tag{5}$$

where k is the coordinate number in fracture plane, and is a damping parameter, which is determined by the statistics of encounter of the fracture fronts with the grain boundaries.

The integration of Eq.(5) gives the behavior of the total number of bond ruptures:

$$N = \frac{K}{\delta}\left(\frac{1-e^{-\delta t}}{\delta} - t e^{-\delta t}\right) \tag{6}$$

The total number of ruptured bonds, which is proportional to the fracture area, is approximately given by

$$\sum N = K/\delta^2 \tag{7}$$

Since the maximum of the $\Delta N(t)$ curve occurs at $t_m = 1/\delta$, we obtain the relation between this time and the total number of ruptured bonds (fracture area):

$$t_m = \sqrt{\Sigma N/K} = \sqrt{S/K} = c\sqrt{S} \tag{8}$$

where c is à constant, whose numerical value lies in the interval 1.5-2.5 for different materials. The flow of acoustic pulses is proportional to the integral of number of ruptured bonds,

$$\varphi = \varphi(N,D)\int N e^{-Dt}\,dt \tag{9}$$

where D is the flow damping constant, which is attributable to the influence of the St.Venant principle and is related to the size of the inhomogeneity field. It can be assumed approximately that $D \approx \delta$.

The flow of elementary acoustic pulses, each of which is associated with relaxation of a single atomic bond, forms an acoustic-emission pulse. If the elementary pulses are summed coherently and the "differentiating" action of the acoustic medium is taken into account, we obtain an acoustic emission pulse of the form

$$U_{aE} = a t e^{-Dt} \tag{10}$$

Eq.(10) may be used for approximation of the acoustic emission pulses taking place for elongate fracture area. For compact area we have more short pulse (Fig.5b)

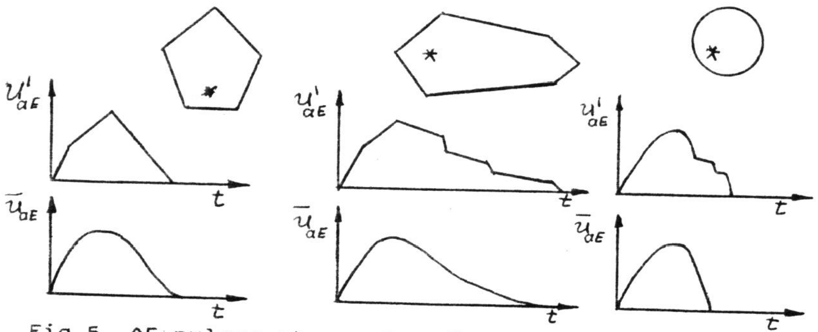

Fig.5. AE pulses shapes for different forms of fractured grains. Upper - grain form, middle - individual pulse shape, bottom - average pulse shape.

it can be approximated, for example, with the next expression:

$$u_{aE} = a t e^{-Dt^2} \qquad (11)$$

For the circle area (for composite material thread) we can propose next expression (Fig.5c):

$$u_{aE} = a \sin \Omega t, \quad 0 \leq \Omega t \leq \pi \qquad (12)$$

It must be born in mind that Eq.(10) is an analytical approximation of the real signal, which usually has a more complex form. However, this approximation, first of all, exhibits the physics of the process, secondly, it can be used to estimate several parameters of the source, including the fracture area {Eq.(8)}.

Testing the action of the resulting void in a solid as a source of radiation with the appropriate source function, we obtain an oscillating pulse of elastic vibrations, whose energy (amplitude) is related to the relaxation volume in the zone of the newly formed void. The time to attain the maximum is related to the fracture area {Eq.(8)}.

Multioscillations of signal we have also due to of many time reflections in construction and influence of the response of transducer (Ivanov, 1991). Experimental studies in which

the shape of acoustic-emission pulses has been determined with sufficient reliability are virtually nonexistent. The determination of the fine structure of the signal entails a number of methodological difficulties such as the solution of the problem of reconstructing the source function from the parameters of a signal transmitted along a complex acoustic channel, the loss of information in signal transmission through the electroacoustic transducer, etc.

The brittle fracture of a solid or part of it (unit, grain, cleavage fragment) proceeds in a coherent way and is accompanied by the radiation of coherent elementary acoustic-emission pulses, which form the acoustic emission pulse. The process of generation of the acoustic radiation is fundamentally similar to the process of coherent optical radiation, and acoustic-emission pulse is similar to a giant laser pulse. The mechanical loading of a solid corresponds to the pump, and the structure of the solid is the analog of the active material in which the pump energy is stored up.

Plastic deformation and ductile fracture are accompanied by incoherent acoustic radiation (continuous emission) and, continuing the analogy with optical phenomena, corresponds to white light with a spektral radiant-energy distribution that is nearly uniform in certain range of wave numbers.

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