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Kinetics of photon radiation formation during deformation and destruction of compact bone tissue

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A comprehensive study of deformation and destruction of compact bone tissue was carried out. Deformation of cylindrical samples was carried out in the mode of constant feed rate of the press plunger. During the experiments, deformation, changes in photon radiation on the surface of the samples and acoustic emission were recorded. It is shown that the initial accumulation of stresses on the relative axis of deformation for the occurrence of a crack on the lateral surface of the sample is the first link in the chain of formation of the micro-cut plane and an indicator of its orientation relative to the axis of the cylinder. The incipient plane of a macro-crack is a zone of increased local stresses, which stimulates the appearance of new microcracks in it. In this case, the exit of the microcrack to the lateral surface of the sample of compact bone tissue (human tibia) coincides in time with the registration of photoluminescence.

Keywords: bone tissue, deformation, photoluminescence, acoustic emission.

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Introduction

Destruction mechanics of various structural materials for recent 20 years, has become one of the most rapidly growing deformable solid mechanics branch [1–3]. Its development is especially intensive and is of high practical importance for study and description of destruction processes in various synthetic composites. However, in addition to these artificial materials, there a several natural biopolymer materials — bone tissues, tendons, etc.. whose destruction is understudied [4–7]. This paper addresses destruction aspects of one of these materials — compact bone tissue which is one of the main components of human and animal skeleton. This tissue forms diaphysial areas in long pipe bones which bear high mechanical loads and more often are exposed to external injury-risk factors. High specific strength, i. e. ratio of destructive stresses to material density typical of compact bone tissue, has been attracting attention of experts on mechanics of materials. This is explained by the fact that high-performance natural biosystems have optimum structure not only in terms of physiological functioning conditions, but in terms of several mechanical behavior and membranology aspects, and macrosystem biophysics [8]. In many modern processes (orthopedic bar manufacturing, stomatology), intensive material exposure methods are widely used — laser impact, high-energy beam treatment, etc. In this case, pressures occur in solid bodies which are referred to as pulse pressures and are distributed over the substance in the form of stress waves or strain waves [9–11]. Stress pulse interaction may cause intensive short-term tension of local material volumes causing typical dynamic fracture — rear separation, in some conditions. This type of destruction has been widely studied in solid bodies and liquids [3] by various methods and pulse load conditions [4].

1. Experimental results and discussion

For the purpose of comprehensive study of macrofraction formation, a cycle of deformation experiments was carried out on cylindrical samples of compact bone tissue.

The nature of fracture initiation and further propagation in compact bone tissue (samples with moisture content higher than 55−70%) was determined according to individual features, structure and dependence on several factors [12,13]. For this, it was essential to chose the type of load, load orientation about elastic symmetry axes of media, load or strain rate, and external configuration of test samples. In case of sample tension loaded along longitudinal bone axis, i. e. along preferred osteon orientation, fracture surface is sloped to this axis at 45 - 90°. At slow loading, so called „extraction“ of individual osteons from interosseous (interfibrillar) substance and formation of non-linear fracture surface. In dynamic loading conditions, the surface becomes smoother. Destruction line in transverse cross section was mostly on external osteon surface or even between plates and very rarely through Haversian canals.

In case of lateral bending, destruction was caused by combined action of tension and compression stresses — osteon tension in tension region of the sample and loss of external layer stability in compression zone. However, actual destruction initiation was observed in the tension stress region [14]. Samples and bone fragments with lateral

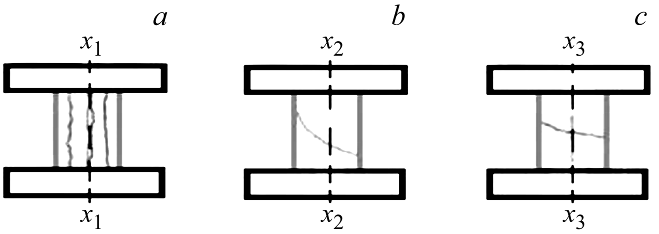

Figure 1. Schematic destruction view of sample torsion about longitudinal (*a*), lateral (*b*) and radial (*c*) axes.

cut in the tension zone were destructed with much lower loss of specific strain energy than solid samples. This is explained by the fact that significant part of specific strain energy is spent for formation of fracture with critical length. At the same time, stress intensity factors necessary for fracture initiation are different for longitudinally and laterally oriented samples. The average stress intensity factor for bone tissue along longitudinal bone axis was equal to 56–60 kgf/cm^2. For torsion of samples with square cross-section, macro destruction occurs when shear stresses in the center of the large side achieve their limit. For samples with previously known round cross-section, fracture locations have not been defined [12,15,16], however, the experiments with these samples detected the type of bone tissue destruction depending on the applied load about the elastic symmetry axes. Destruction of samples cur along the longitudinal bone axis occurs gradually with initiation of multiple microfractures along the osteon system (Figure 1).

Torsion test sample is divided into separate osteons or groups of osteons (Figure 1). Symmetry axes are fragile and destruction surface is directed towards the sample axis at 45°. It should be noted that the type of bone tissue destruction varies depending on the age and possible bone abnormalities. Repeated load tests have shown that destruction of compact bone tissue is of peculiar nature that differs from many artificial materials. Therefore, to evaluate the type of damage accumulation in compact bone tissue strain, mechanical luminescence method was used. For torsion of samples with square cross-section, macroruptures occur when shear stress in the center of the large side achieves its limit.

Photon emission method [5] (luminescence) is associated with recording free-radical recombination during internal bond rupture and gas discharge in condition of formation of new surfaces, i.e. microfractures [6]. pronounced photon emission effect in bone tissue was only defined at the strain stage. The main feature of destruction of this tissue in old age was associated with dramatic reduction of specific strain energy necessary for destruction and with formation of smoother fracture surfaces. The latter indicates reduction of rheologic bone adaptation to external impacts with age increment. Figure 2, *a* shows destructive shear strain variation curves $\sigma_i/d\sigma_i$ and destructive specific strain energy U vs. age Y curves. As can be seen, in the age of 80, value U decreases by more than a factor of two compared with the age of adolescence. irreversibly spent specific strain energy W and total number of acoustic emission pulses (AE) N vs. relative stress is shown in Figure 2, *b*. Comparison of curves $N(\sigma_i/d\sigma_i)$ and irreversibly spent specific strain energy $W(\sigma_i/d\sigma_i)$ shows that there is high positive correlation between them ($g = 0.95$) (Figure 2, *b*). This confirms the assumption of energetic nature of the acoustic emission process. However, during bone tissue strain process long before full destruction, initiation and gradual accumulation of microfractures take place in the bone tissue.

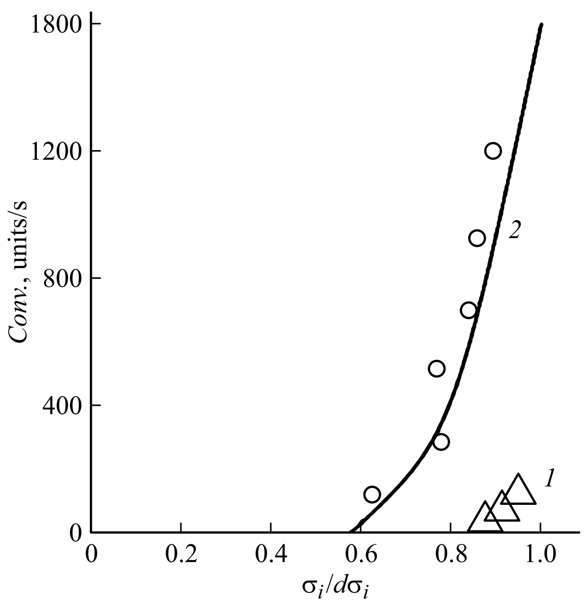

Figure 3. Deformation stages and DL photon kinetics in bone tissue (*1*) and glass fiber (*2*).

To measure and record the initiation and gradual accumulation of microfractures accompanying acoustic and photon emission events, we have made a special system with spectrographic optical-band instrument with high record precision [14,17,18].

Acoustic emission method is associated with recording of not only strain noises in the test material, but also noises caused by further propagation of structural defects — both dislocations and fractures in strain. The main record parameters were addressed: total amount of acoustic pulses N observed in the specific strain range, signal emission intensity N, i.e. the number of pulses per unit time and processing of some noise interference. Since the total number of pulses is a nonlinear function of the stress intensity factor, N allows to judge about the approach of destruction.

During photon emission treatment of experimental bone tissue data, the pronounced photon emission effect in bone tissue was found to be observed only at the final deformation stage ($\sigma_i/d\sigma_i \geq 0.96$). luminous intensity at this

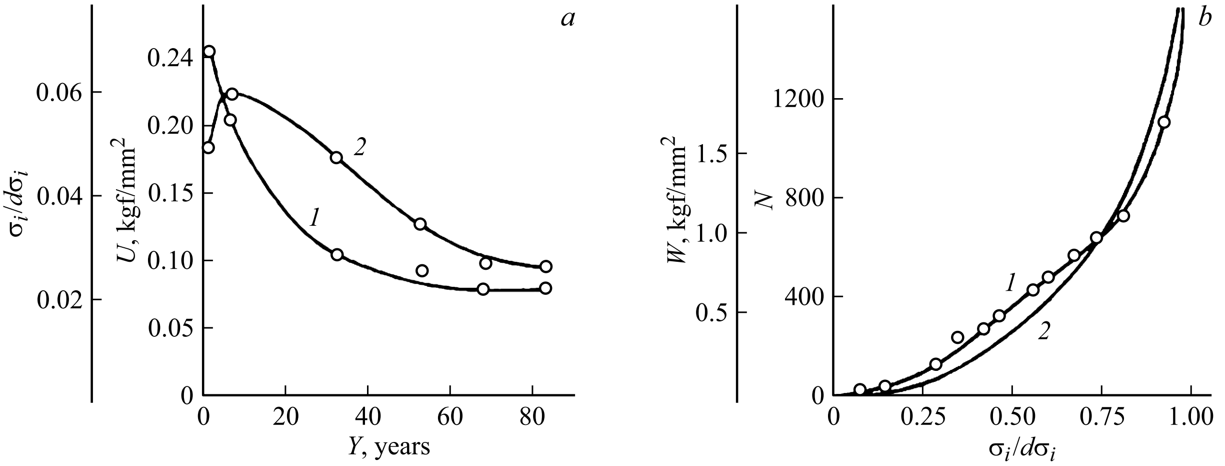

Figure 2. *a* — destructive shear strain $\sigma_i/d\sigma_i$ and destructive specific strain energy U vs. the age Y: *1* — along longitudinal bone axis, *2* — in lateral direction; *b* — irreversibly consumed specific strain energy W (*1*) and total number of pulses AE N (*2*) vs. relative stress.

stress level was 49 conv. units/s, and achieved 68 conv. units/s during destruction (Figure 3, curve *1*).

At the same time, in artificial composites, emission intensity was much higher. For example, in glass fiber reinforced with layers at ±45° to load direction, photon emission is initiated at $\sigma_i/d\sigma_i = 56 \pm 2.7\%$ from destructive deformation and further accumulation of deformation luminescence (DL) takes place at 38 units/s. Total amount of DL achieves 1780–1810 conv. units (Figure 3, curve *2*). Study and comparison of DL in glass fibers have shown that emission (photon emission) in them starts at much lower deformation levels than in compact bone tissue. This indicates better bone tissue structure and the absence of high internal stresses compared with artificial materials.

Conclusions

The detected features of compact bone tissue destruction allows to make a conclusion that composite multistage structure of this biopolymer material ensures high bearing capacity. It is shown that in compact bone tissue deformation with constant rate at room temperature, DL probably occurs in the form of single electron and photon emissions. DL occurs at the final deformation stage — at compact bone tissue destruction stage. Intensity grows with increase in DL stress. We suppose that in this case released elastic strain energy may become sufficient for macrodestruction initiation. Further study and comparisons of biopolymer material and bone tissue microdestruction at different structural levels certainly allow to develop the ways to improvement of reinforcing structures of artificial materials.

Conflict of interest

The authors declare that they have no conflict of interest.

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