Electromagnetic radiation method for identification of multi-scale fracture and dynamic parameters of thin fibers

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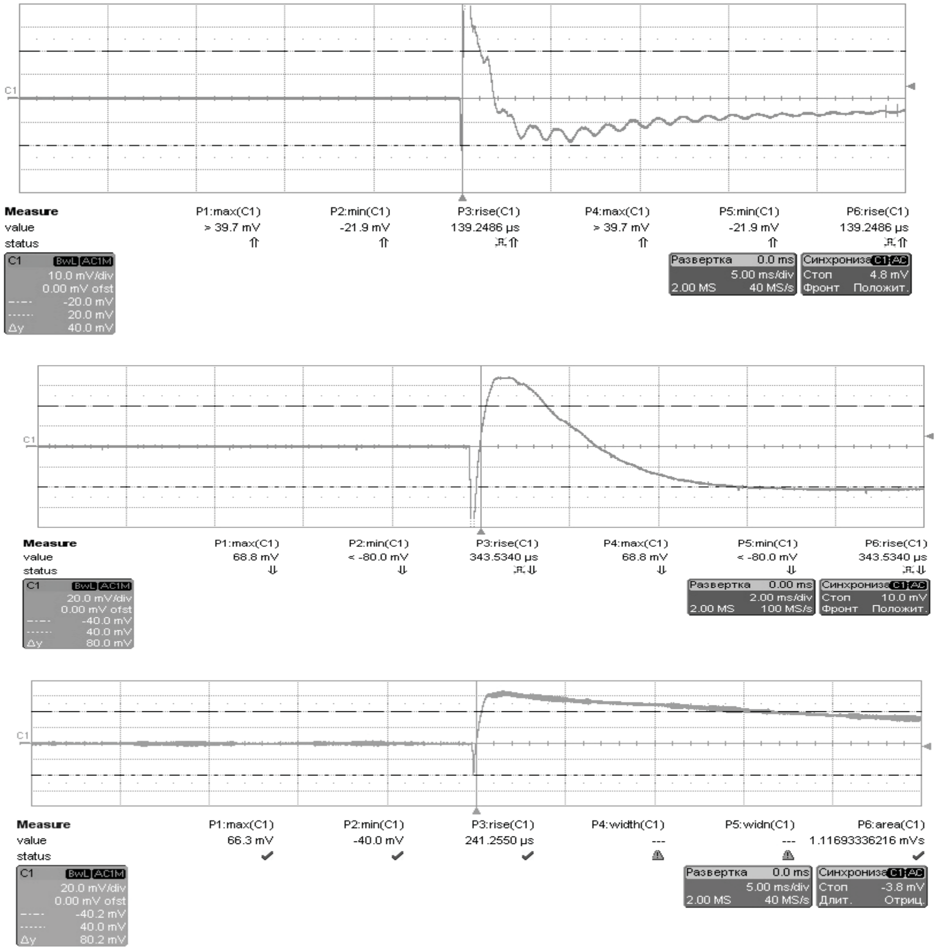
Abstract. A review of the experimental results on measurements of electric signals emitted during tensile failure, transversal oscillations and wave phenomena in thin fibers is presented. The special experimental systems have been devised with this aim. The electromagnetic radiation (EMR) were recorded by an antenna over radio range of frequencies. First, the behavior of electric component of EMR emitted during tensile fracture of the silica glass fibers and the influence of scale size are discussed. Next, the electrical method for obtaining the nonlinear stress-strain curves for the fibers by means of registration of both frequencies of the fiber transversal oscillations (as an elastic string) and elongations has been developed. Also, the method for the wave velocities and dynamic Young's modulus determination using the EMR-effect has been suggested and applied to the copolymer and nylon fibers of variable diameters.

Introduction

Previous numerous investigations have demonstrated that any dynamic process in material or failure excite electromagnetic radiation. Many attempts to explain the physical mechanism of the EMR emitted during macroscopic failure of various materials or wave propagation in metals was proposed (see recent reviews in [1-3] and papers [4-10]. Generally, the measurements of EMR can serve for identification of oscillations, waves and fracture. The objective of the present paper is to develop this method for registration of these phenomena in application to nonconductive micro fibers and for determination of their constitutive parameters and functions. A review of data resulting from the three type of runs is presented below. First, the tensile fracture phenomena with the silica glass and copolymer fibers were registered using the EMR-effect. The peculiarities of the electric component of EMR including influence of the scale size are discussed. Then, a series of tests on transversal oscillations of the copolymer fibers at given tension was carried out. Here an electric charge was distributed along the surface of each fiber and its vibration motion was registered by antenna (this is not the EMR). The latter lets us determine the frequencies, forms and damping factor. In addition, by measurements of the pare, frequency-elongation, and by using the classical theory of elastic string, the nonlinear loading-unloading stress-strain curves may be obtained. Last, the wave speeds are measured by the EMR method using the two special small antennas placed at the distance l along the fiber. After notching-failure this fiber preliminary loaded by given tensile deformation, the unloading waves excite the EMR that is detected by the antennas. Analysis of the signals gives the time it takes a wave to travel from the one gage to another and then the wave speed is simply determined. The essential dependence of the longitudinal wave speed on the initial deformation and diameter of the fiber was revealed.

EMR during fracturing

Experimental study of thin fiber fracture is of scientific interest. Because of μm scale of their diameters, it is very hard to use the traditional methods and the EMR method being very sensible and non-contact appears to be more suitable. Note that the previous works on this topic were only devoted the study of a macro solid fracture. Experimental system created aims to measure the EMR emitted during the fracture process of very thin fibers at tension and consists of a varied antenna (gage), crabs for fixing a fiber, the current repeater, frequency range up to 10 MHz, low-noise micro-signal amplifier, frequency range up to 20 MHz, and the computer based digital storage Le Croy Wave Surfer 422, frequency range up to 200 MHz. The designed antenna was suitable for EMR signal in radio range and placed along with fixed fiber in the electrostatically shielded *Al* box to minimize any external electrical influence.



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Measure   P1:max(C1)   P2:min(C1)   P3:rise(C1)   P4:max(C1)   P5:min(C1)   P6:rise(C1)
value     > 39.7 mV    -21.9 mV     139.2486 µs   > 39.7 mV    -21.9 mV     139.2486 µs
status    ⇑            ⇑            ⇑             ⇑            ⇑            ⇑
C1  BwL AC1M                        Развертка     0.0 ms      Синхрониза C1 AC
    10.0 mV/div                                   5.00 ms/div Стоп         4.8 mV
    0.00 mV ofst                    2.00 MS       40 MS/s     Фронт        Положит.
-·-·- -20.0 mV
----- 20.0 mV
Δy    40.0 mV
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Measure   P1:max(C1)   P2:min(C1)   P3:rise(C1)   P4:max(C1)   P5:min(C1)   P6:rise(C1)
value     68.8 mV      < -80.0 mV   343.5340 µs   68.8 mV      < -80.0 mV   343.5340 µs
status    ⇓            ⇓            ⇓             ⇓            ⇓            ⇓
C1  BwL AC1M                        Развертка     0.00 ms     Синхрониза C1 AC
    20.0 mV/div                                   2.00 ms/div Стоп         10.0 mV
    0.00 mV ofst                    2.00 MS       100 MS/s    Фронт        Положит.
-·-·- -40.0 mV
----- 40.0 mV
Δy    80.0 mV
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Measure   P1:max(C1)   P2:min(C1)   P3:rise(C1)   P4:width(C1)   P5:widn(C1)   P6:area(C1)
value     66.3 mV      -40.0 mV     241.2550 µs   ---            ---           1.11693336216 mVs
status    ✓            ✓            ✓             ⚠              ⚠             ✓
C1  BwL AC1M                        Развертка     0.0 ms      Синхрониза C1 AC
    20.0 mV/div                                   5.00 ms/div Стоп         -3.8 mV
    0.00 mV ofst                    2.00 MS       40 MS/s     Длит.        Отриц.
-·-·- -40.2 mV
----- 40.0 mV
Δy    80.2 mV
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Fig. 1. Examples of double pulses during fracture of glass fibers, $d = 18, 10, 6.5$ μm

Silica glass fibers ($d = 6.5, 10, 18, 150$ μm, 12 mm length, $\rho = 2.58$ g/cm^3, 95 GPa Young's module, and 2.5, 2.0, 1.5, 0.5 GPa tensile strength, respectively) were selected for investigating the EMR emission during tensile fracture. The typical electric signals, voltage U vs time t, are shown in Fig. 1 and consists of double pulses (the negative and positive phases) that differ greatly in lengths and magnitudes. To all appearance, the main cause of the EMR emitted is not the fracture process by itself, but its aftereffect, the subsequent elastic unloading wave propagation, as far as the magnitudes of pulses is not related to the entire area of the fractured cross section and would remain to be of the same order while this area dramatically changes. The such factors as the dispersion in strength, the surface and structural imperfections and the residual stresses influence on the large dispersion of EMR magnitudes. It is of interest that sometimes the oscillations are observed along the major signal curve, which corresponds to bending vibration of the *fiber remain* fixed in crab as an elastic cantilever. Last, the polymer fibers demonstrate qualitatively the same EMR pulses during the fracture-wave process.

Fiber oscillations tests

A series of tests was carried out on transversal oscillations of copolymer fibers of varied diameters. Each was preliminarily artificially charged along the hole surface and elongated to a given value. Experimental system is the same, but here antenna was a metal aligning plug. The oscillations were excited by hand using a thin wood stock.

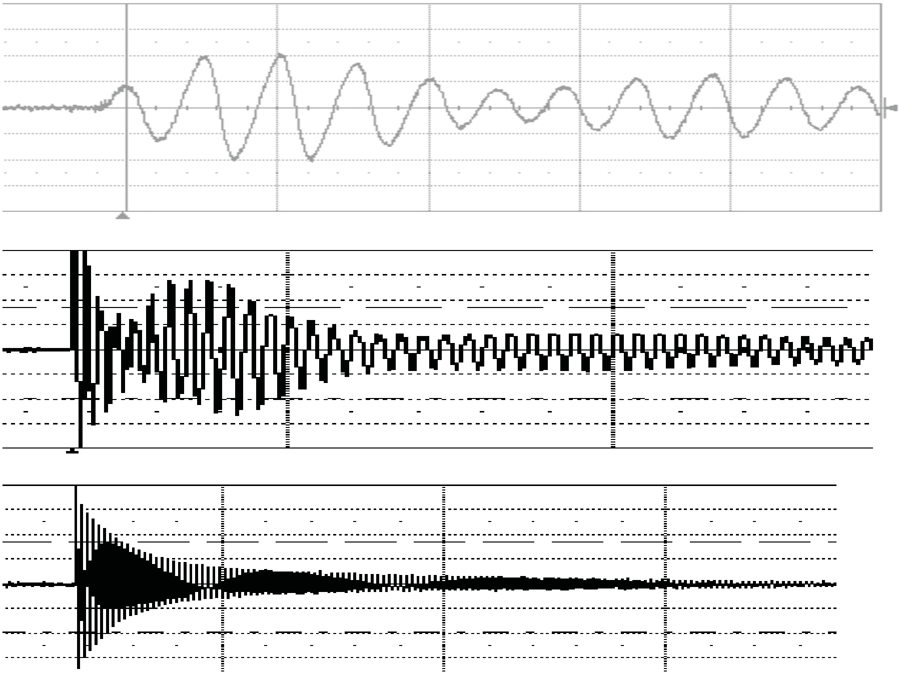

Fig. 2. Examples of oscillations with pulsation caused by rotation of the oscillation plane and with damping

During many tests with the copolymer fibers (Japan fishing line, Nikko Vexter (NV); $d = 60$, 80, 100, 300 μm, $L_0 = 20\ mm$) it was established the following. The oscillations of the fibers as elastic strings do not recorded without preliminarily coating a charge on to fiber face. No influence of the value and sign of this charge has been revealed. The electric signals registered adequately reflect forms, frequencies and damping factor of the oscillations (see examples in Fig. 2, $d = 300$ μm). Also, by measuring the parameters of these oscillations, some mechanical behavior of polymeric materials can be clarified. Thus, by knowing the frequency, f, as a function of deformation, ε, the fiber stress, σ, can be determined by formula $\sigma = 4f^2(\varepsilon)L_0^2\rho_0(1+\varepsilon)$, which follows from the classical theory for elastic string. One example of diagrams $f = f(e)$ and $\sigma = \sigma(e)$, e=100% ε is shown in Fig. 3. Note that the direct measurement of small forces in the case of very thin fibers has run into difficulties, but the measurement of the pare, frequency-elongation, instead of the pare, force-elongation, can help to reach the required accuracy. Furthermore, this method can be applied to nondestructive control technology in micro-nano scales [10].

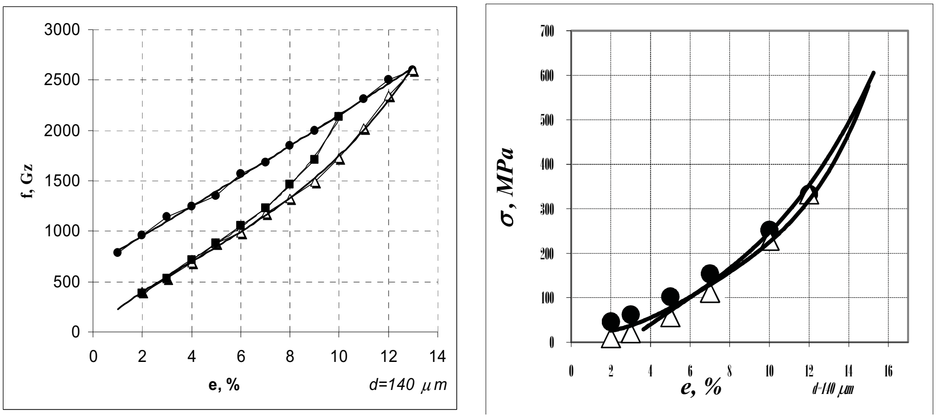

Fig. 3. The loading (●) and unloading (Δ,■) diagrams $f = f(e)$ and $\sigma = \sigma(e)$ in comparison to their straight measurement (—).

Measurement of wave speeds and Young’s modulus

Here we use the former copolymer fibers and the new nylon ones (Japan fishing line, Broad Nylon Monofilament (BNM); $d = 60, 100, 180\ \mu m$). These nylon fibers differs dramatically in the tensile behavior. As it follows from the loading-unloading stress-strain curves with the endurance tests (example see in Fig. 4), they can be clearly defined as viscoelastic-plastic. For both type of fibers it has been proved that the characteristic relaxation time of the stresses is several seconds in order, but this grows as the deformation e tends to its rupture value.

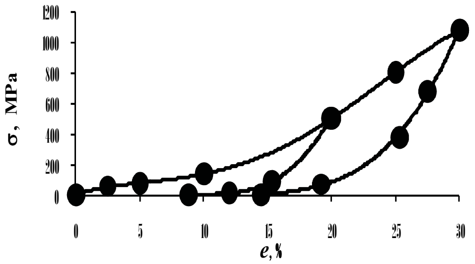

Fig. 4. Stress-strain curves with the endurance tests of the nylon fibers, $d = 100\ \mu m$

Overall the following wave events after tensile cutting-failure of fibers are detected. As indicated above concerning the glass fiber, the double major EMR signal is caused due to the unloading wave propagation and sometimes, when the relation l/d is not too large, the transversal elastic vibrations of their remains in crabs are reflected in the oscillograms as a secondary effect. Otherwise ($d \le$ 10 μm, $l = 20$ mm), instead, these remains exhibit the large nonlinear bending. By analyzing electric pulses emitted during propagation of waves in the copolymer and nylon fibers, mainly the faster longitudinal wave and sometimes the slower transversal wave might be distinguished. Once the former wave reflects from crab as a compression wave, the loss of stability (like with the impact) leads, firstly, to the transversal wave emergence and, secondly, to the highly crumpling ($d <$ 0.2 mm) or to nonlinear bending ($d \ge$ 0.2 mm).

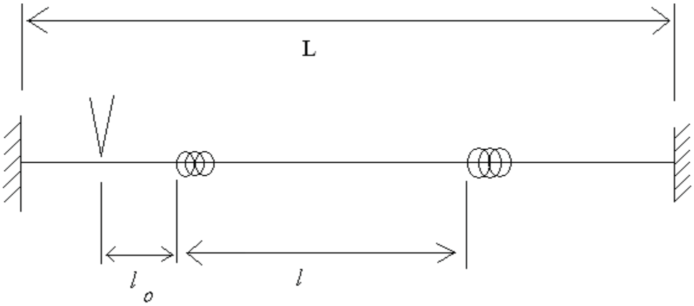

Fig. 5. Schematic drawing of the gauges disposed along a fiber in the wave velocity tests

The new method of the wave velocity test is suggested. To do that, two gages are disposed along a fixed fiber (under a given tensile deformation e) at the distance l, as it is shown in Fig. 5. Each gage consists of three loops of isolated copper wire of small dia less then 1 mm and therefore operates as a spot antenna. After notching the fiber by a sharp blade at a distance l_0 from the left-hand gage up to the intensity, when the tensile force reaches the limit for this damaged system, the fast failure arises and then the unloading elastic waves start from the point of failure. Since each gage begins to operate and to transform the electric signal to Le Croy screen only when the wave front approaches close to that, the duration between the first phases of these signals determines the time, it takes the wave to travel from one gage to another. The typical signals, $U = U(t)$ are shown in Fig. 6.

Thus the wave velocity is $c = l/t_0$. As far as the polymers are the hereditary elastic or hereditary elastic-plastic media and any fast processes in are usually described in the context of elasticity, the theory of elastic waves in rods is applied here. Due to this theoretical ground, we write

$$c = c_l = \sqrt{E/\rho} \quad \Rightarrow \quad E = \rho c_l^2, \tag{1}$$

where c_l is the longitudinal wave speed , E is the Young's module and both correspond to the fast unloading from a prescribed point on the "static" diagrams $\sigma = \sigma(e)$ to $\sigma = 0$.

The above mentioned "elastic theory" conjecture have been put to various tests. In particular, the fiber's free end motion after the tensile failure was fixed by high-speed video camera and thus the mass velocity becomes to be known. From the wave and mass velocity measurement it was established that the linear elasticity remains valid until the initial deformation e is not large (e<10%). Otherwise, the nonlinear theory of elasticity has to be incorporated.

The experimental data on $c=c(e)$ and $E=E(e)$ are presented in Fig. 7, 8. Each mark means the value averaged over 10-15 test data. It follows that rigidity of any fiber essentially grows as the initial deformation e grows. As this can be also seen, the size effect is essential. Thus, the difference in c reaches 1.1 km/s for the copolymer fibers when d changes from 280 to 60 μm, but in the case of nylon, the size effect disappears at the diameter being larger than 0.12 mm. It is of interest that in spite of very different rheology and ultimate deformations of the fibers tested, the approximating trends for $c=c(e)$ points are always the straight lines

$$c=A+Be \tag{2}$$

	Copolymer fibers			*Nylon fibers*		
A	2. 242	2.114	2 .467	1. 29	0.9022	0 .9022
B	0.1434	0.2253	0.2421	0.12	0.1117	0.1115
d, мм	0.14	0.1	0.06	0.06	0.12	0.18

and, accordingly to Eq. 1, 2, $E=E(e)$ are quadratic functions. Consequently, these laws are inherent in a certain class of the fibers. According to given values of E, the dynamic unloading up to $\sigma=0$ gives rise to the jump of deformation $\Delta e = e - e_* = 100\% \ \sigma(e)/E$, that is well less than the nominal one, e. For example, for the copolymer fiber of $d=100\,\mu m$, e =12% we found out E =28 ГПа, σ=0.5 ГПа, $\Delta e =$ 1.8% << e. The residual deformation e_* dies out comparatively slowly after the dynamic process.

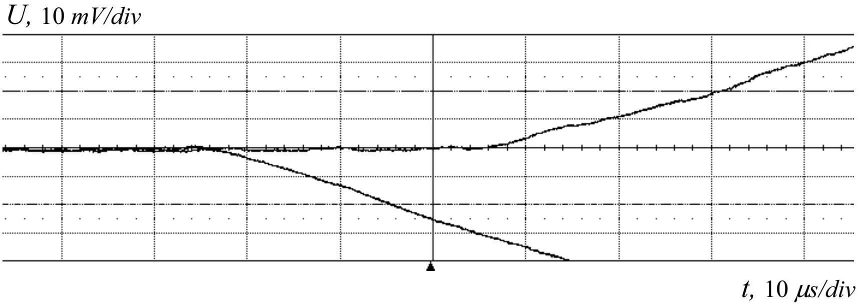

Fig. 6. Typical EMR signals from two gauges at d=100 μm, e=5%, l=100 *mm*

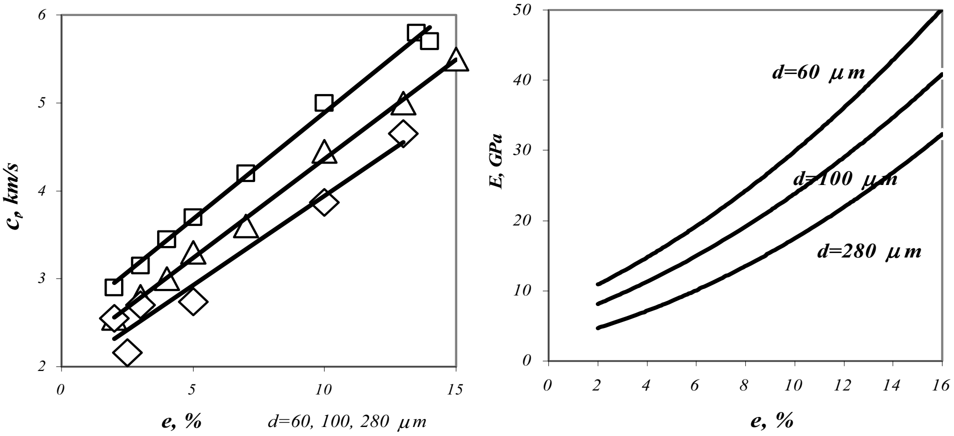

Fig. 7. Longitudinal wave speeds and Young's modules vs e for the copolymer fibers

□ – d=60 μm, Δ – d=100 μm, □ – d=280 μm

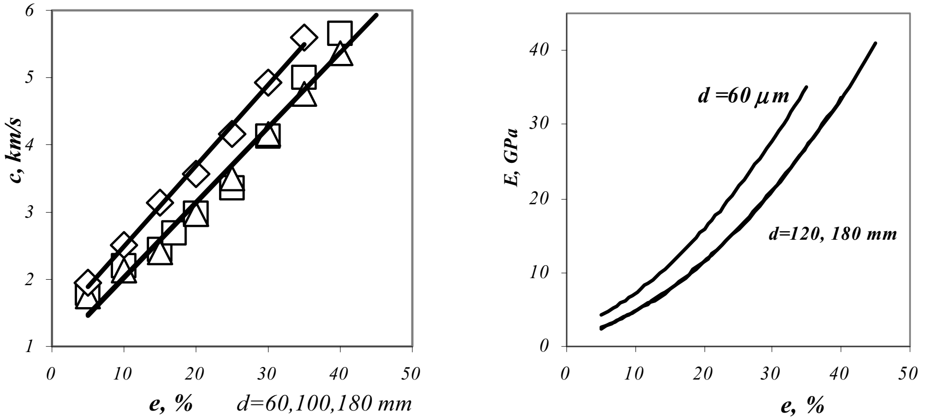

Fig. 8. Effect of initial deformation on wave speed and Young's modules for the nylon fibers

□ – d=60 μm, Δ – d=120 μm, □ – d=180 μm

Conclusions

The purpose of the research was to examine a feasibility of using the electromagnetic radiation as a tool for investigation of various dynamic processes with micro fibers and as a result, for obtaining fundamental knowledge about their mechanical behavior. It is shown that the extension of EMR-effect in application to thin fibers can give the chance to recognize the failure, waves and oscillations. Furthermore, this has much potential for yielding information about the material parameters and functions, such as the stress-strain curves, wave velocities and Young's modules.

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References

[1] A. Misra and A. Kumar: *Int. J. Fracture*, V. 127 (2004), p. 387.

[2] J. Goldbaum, V. Frid, D. Bahat and A. Rabinovich: *Meas. Sci. Technol*, V. 14 (2003), p. 1839.

[3] V. Frid, A. Rabinovich and D. Bahat: *J. Phys. D: Appl. Phys.,* V. 36 (2003), p. 1620.

[4] V.M Mineev and A.G. Ivanov: *Advat. Phys. Sci. USSR*, Vol. B119, No. 1 (1976), p. 75.

[5] M.I. Kornfeld: *Physics of Solids*, Vol. B12, No. 1, (1970), p. 318.

[6] M.Ya. Balbachan and E.I. Parkhomenko: *Proc. Acad. Sci. USSR, Physics of the Earth*, No. 8, (1983), p.104

[7] V.V. Viktorov, Yu.V. Kulinich and A.S. Chursin: *Proc. Acad. Sci. USSR, Mechanics of Solids*, No. 1 (1982), p. 183.

[8] A. Misra: *Phys. Lett.* Vol. 62 A, No. 4 (1977), p. 234.

[9] E.A. Deviatkin: *Pisma v ZhTF*, Vol. 1**6,** No. 3 (1990), p. 51.

[10] I.V. Simonov, A.A. Sirotin, I.M. Smirnov and A.V. Tyanin: *Pisma v ZhTF*, Vol. 14, (2007), p.19.