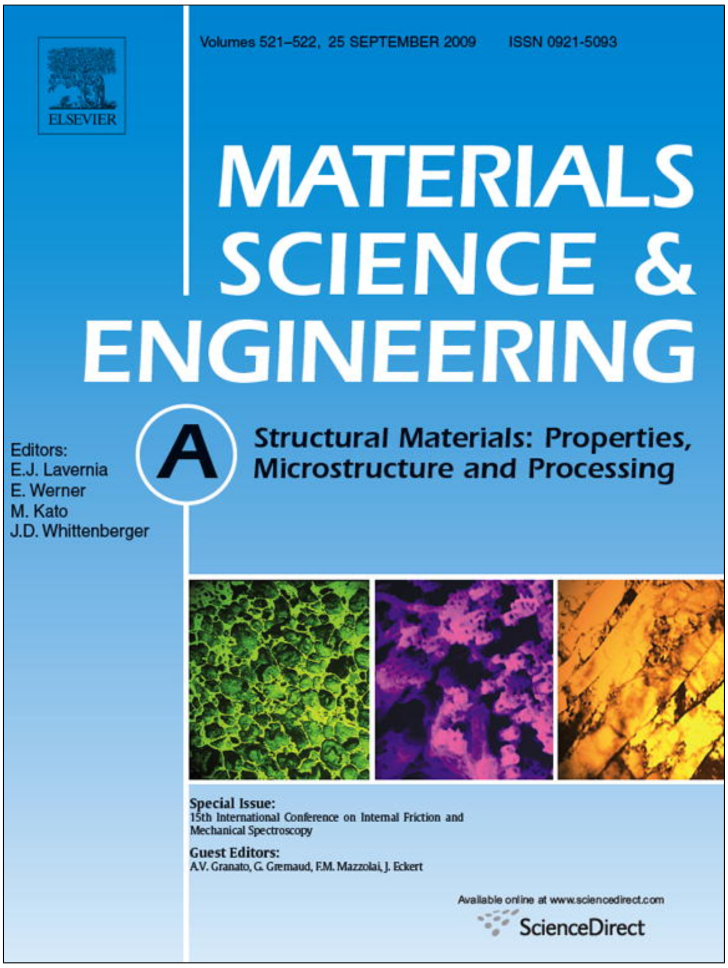
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The effect of crossed electric and magnetic fields in loaded rock specimens

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ABSTRACT

The idea of the work is to demonstrate that impacts of crossed electric and magnetic fields (Cr.EMF) are applicable to study the rate of internal fracturing processes in loaded rock specimens. Our previous experiments with rock specimens loaded by a press have revealed the effect of acoustic emission (AE) activity increment caused by electric pulses. The experiments have been held on a noiseless rheological machine available at Bishkek Geodynamic Research Center—RS RAS. We analyzed the temporal dependence of AE activity during exposure to crossed electric and magnetic field; the compressive load being constant. The effect of AE stimulation by power pulses (triggering) has been verified. AE measurements have confirmed the existence of explicit response to both kinds of Cr.EMF pulses: solitary pulses with major amplitudes of E and B and periodic long-term pulses of minor E and H amplitudes. The comparison of recent and previous results on AE triggering by external electromagnetic (EM) fields has demonstrated that two modes of activation can be distinguished. Both kinds of AE variations (responses) are manifestations of change in internal friction (microcracking and kinetics of other defects).

1. Introduction

It is well-known that strong enough electric and magnetic fields have an influence on plastic straining of nonmetallic solids (particularly on the plasticity of alkali-halogenic crystals [1–4]). Effects such as changes in internal friction and conductivity under electric fields were in a focus of the quoted works. A relationship between these effects and dislocation motion was revealed. According to the previous works some increment of plasticity occurs when the strength, E, of the electric field is of the order of 10–100 kV/m at least [1,3], or when the magnetic inductance, B, exceeds 0.1 T [4]. One can assume that EM fields of such minor values of E or B components may contribute to inelastic straining (microfracture) which can evolve in micro- and meso-scales of length. AE method allows detection of any (even very weak) change in the straining/microcracking rate in semi-brittle solids (rocks). So, temporal variations of AE activity may be considered as a signature of the effect of physical fields applied externally, i.e. as induced (or triggered) changes in a rate of accumulation of structural defects, microcracks in particular. Actually, numerous experiments with pristine rocks samples and artificial solids (such as concretes and water-containing ceramics, to simulate terrestrial materials) subjected to compressive load and to additional action of EM field have revealed AE activation as a response to the EM field [5,6]. Our previous works [7,8] specified that an increment in the AE activity due to EM field pulses occurs, provided the fixed compressive load over tested rock specimens is from 0.75 to 0.95 of the maximal value (fracture stress). We have tested a number of specimens, made of materials with different elastic and piezoelectric properties: granodiorite, quartzite, granite, halite, and zirconium oxide ceramic. We have assumed that the effect of AE electrostimulation is related to inelasticity of terrestrial materials under stressed-strained conditions, which correspond to a dilatation (caused by tensile microcracks) rather than to the formation of a main crack. But the physical mechanism of the electromagnetic influence on AE is not completely clear. The excitation of microvibrations and acoustic waves is the most probable candidate to explain the responses of AE, since the effect of vibrations (even very small) on microcrack growth has been already proved [9]. It should be noted that the piezoelectric effect cannot be responsible for this electric to acoustic transformation of energy because the values of piezoelectric modulus of rocks studied [7,8] are too low. There are some models which could describe a mechanical stress generation under external electrical influence in loaded rock massifs [10,11,12]. But no proposed model is able to reply to the following question—do defects of minor or major size mostly contribute to the increment of the AE activity under an electromagnetic action? Meanwhile, this issue is of great significance from the viewpoint of geophysical and seismological applications of aforementioned effect of microcracking stimulation. Another debatable aspect concerns general rules and specific features of the effects triggered by the EM field. Is it valid, that such a triggering (identified by

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AE response) entails transition of rocks material to the relaxed state?

As noted in [13,14] a transition from diffusive (uniform) microcracking to cracks clustering involves serious changes in the succession of defects nucleation and corresponding flow of AE events. The process of microfracture becomes nonrandom during such transition [13], so Poisson distribution of the AE events number over temporal intervals is terminated. From the viewpoint of microcracking, loads to cause rocks dilatant strains (at which AE responses to electric pulses were observed [7,8]) correspond to the beginning of the clastering stage. This stage may be characterized by intensification of dislocation processes and re-orientation of microcracks planes from axial (parallel to the action of main compression) to oblique. According to [15] such re-orientation results from the creation of new inclined cracks forming jumpers between ones with axial planes.

Cr.EMF allows the control of direction of momentum transfer that is equivalent to ponderomotive force exciting elastic microvibrations. A configuration of sources of electric and magnetic field that provides parallel direction of Umov–Poynting vector and compressive load is seemingly the most proper for experiments to study the influence of the above crossed fields over microcracking. Let us explain this aspect. The Cr.EMF action stimulates the drift of positively and negatively charged particles (point defects such as impurity ions and vacancies in the same direction. The dilatant straining stage of the rock specimen means the formation of strengthening and softening zones. The strengthening occurs near specimen edges in contact with the loading platens, the softening is near the middle plane. Usually charged particles in dielectric rocks are concentrated on crack faces and along dislocation lines. The diffusion of charged particles towards the radial dilated domains (softened zone) may contribute to the relaxation (this is a factor acting against dilatancy). Also it may influence the dislocation motion, i.e. plasticity. But the diffusive flow from a zone of strengthening strikes barriers. The Cr.EMF can stimulate axial flow of charged particles (towards softened zone) if Umov–Poynting vector is oriented near the axial direction. Additional action of Cr.EMF with such direction of Umov–Poynting vector is expected to modify rate of microcracking and/or plastic straining of rocks specimen under some values of uniaxial compressive load.

Motivated partially by the above issues we developed investigations on AE of rock specimens. The aim was to study the influence of pulses of Cr.EMF field on the parameters of the AE. The main obtained results are described in the present paper.

2. Experimental set-up and procedure

An experimental study of electromagnetic-acoustic effects involves the creep test of specimens of rocks and of artificial heterogeneous materials burden by uniaxial compression. We described in details [9,10] the technique of long-term experiments on spring rheological press UDI (designed by Stavrogin [15]) with application of external power actions. Recently, we have constructed the lever machine UDI-L (Fig. 1a and b) of 35 tons compressive load on the basis of load-carrying components of the UDI press.

The main advantage is that a lever press provides noiseless conditions at all times of the test, including sessions of fixed compressive loads and load increments by the addition of the weight on a longer side of the lever. This allows continuous AE recording during stepwise change in main load, meanwhile a spring press is actually noiseless only during constant load sessions, after clamping the displacement of compressed working spring by a screw and nuts. Besides, we remark that the effects of weak external fields cannot be studied on an usual hydraulic press because its drive inevitably produces a lot of noise. We tested intact samples of granite Westerly (parallelepiped with sides 52 mm × 57 mm × 128 mm) during new experiments on the lever press with Cr.EMF (Fig. 1c).

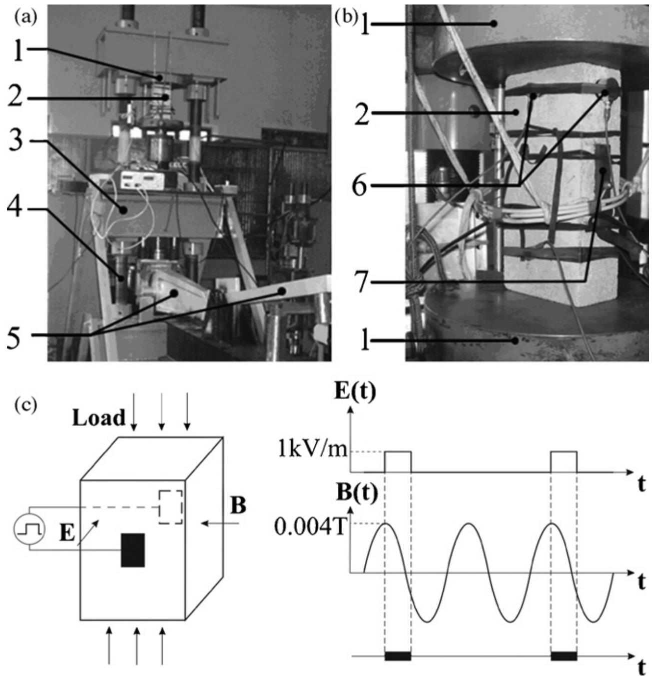

Fig. 1. (a) Lever machine UDI-L, (b) specimen installed for tests. (c) Scheme of experiment with Cr.EMF: at the left—the geometry: directions of main compression (vertical), electric field *E*, and magnetic inductance *B* are orthogonal, at the right—synchronization of periodical electrical pulses (G5-54) with AC generator supply to magnetic coil. Denoted elements: 1, loading platen; 2, specimen; 3, cross-arm; 4, supporting rod; 5, lever units clumping nut; 6, AE sensor; 7, electrode.

Tested specimen was located on the lower platen. The spherical joint, integrated with lower platen, assured the parallel alignment of specimen and compression axis. AE sensors were applied to a lateral surface of the specimen. AE signals (wideband 80 kHz to 2 MHz) after amplification and filtration were used to perform the triggering of recording equipment–ADC (CAMAC standard). The measuring system operated in a waiting mode. This means that a recording starts every time when the signal magnitude exceeds threshold. Inherent noise of the AE channel sets up the value of threshold. The value of threshold was kept equal nearly 1.5 times the root-mean-square of the noise to avoid a false triggering. Additional electric power impacts were supplied by external sources during a deformation session with constant level of compressive load.

A magnetic coil supplied by AC sinusoidal current of the G3-112 generator was the source of additional magnetic field with nearly 0.004 T maximal amplitude of inductance. The coil was placed near lateral surface of a rectangular specimen so, that the induced magnetic field was approximately orthogonal to electric one produced by electrodes fastened to the other (transversal) facets (see Fig. 1c). Alternative magnetic field was used to avoid negative bias of the ferromagnetic elements of the press. The phases of generators to electric and magnetic supply were synchronized with the help of a triggering unit. The unit produced a triggering signal to start G5-54 generator when the current in the magnetic coil reached the maximum. Just after the end of the electric pulse of G5-54 the triggering unit allowed no new pulse as long as a specified dead time (nearly half period of AC sinusoidal current of the magnetic coil supply) was over. So, the frequency of the electric field induced in the specimen was two times less than that of the magnetic field (Fig. 1c). It should be emphasized that the direction of the dynamical force and the vector of energy flow remained the same during the session with action of crossed *E* and *B* fields. In contrast to previous experimental conditions (mainly electric action in addition to compressive load) we could control the value of the energy influx, W, to the specimen during the session with impacts of Cr.EMF; the W being the product of Umov–Poynting vector, $P = [E, H]$, by the total duration of the Cr.EMF pulses. In the reported experiments granitic and rock salt specimens were biased by Cr.EMF pulses, the peaked electric strength of which being slightly less than that during sessions with mainly electric impact. Meanwhile, the energy influx due to Cr.EMF exceeded considerably a typical level of W in that previous case.

In addition to computation of usual AE activity (the based informative parameter) we determined the rate of accumulation of AE events of major and minor magnitudes. We separated the flow of AE signals on 2 groups called “strong” and “weak”. AE signals with amplitudes above the given discrimination level were considered as “strong”, the other signals as “weak”. The program of the numerical discriminator, working with records of AE signals waveforms, was used. We prescribed the level of the discriminator so, that the numbers of strong and weak AE events per second (the selective activity parameters) were comparable, say the difference between their trends should be less than 50%. Furthermore, we considered a distribution of flow of AE events over temporal intervals of a chosen length (TICL) and compared actual distributions with some models of random processes (Poisson, Poya and gamma distributions). An interval of 5 s duration seems to be optimal TICL for typical mean level of AE activity of 1–5 events per second. Also we specified the length of moving window (150 TICLs) and the lag (10 TICLs) to visualize a variation in AE events distributions.

3. Results and discussion

Previous experiments performed with different kinds of rocks under creep test in the presence of an electromagnetic field [9,10] revealed the effect of an energy release increase (relaxation). These fundamental results were established in terms of AE activity as a parameter. In the experimental series held at RS RAS [9,10] AE activity responses with considerable increments of AE (exceeding triple level of AE root-mean-square over steady background) have occurred in 22 cases out of 26 sessions. The responses were observed when the value of main compressional stress was from 0.7 to 0.95 of the fracturing stress for given specimen. Temporary activation of AE (the response) and correspondent growth of accumulated energy release were followed by a partial relaxation of the material. Experiments with additional action of Cr.EMF demonstrated again the existence of interval of compressive loads under which the sensitivity of rocks was very high.

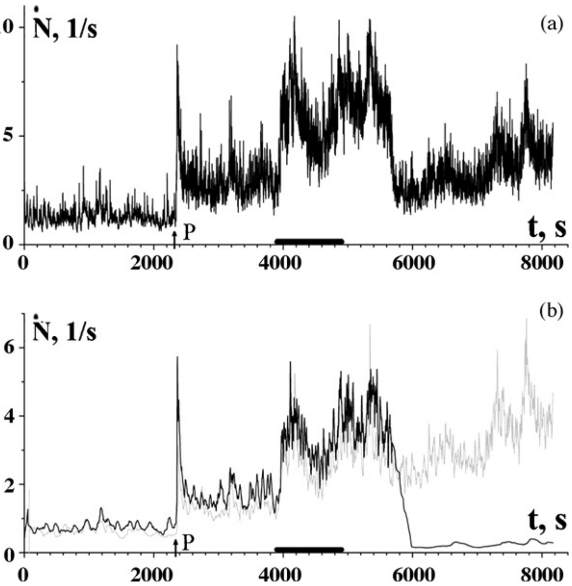

Fig. 2. (a) Temporal plot of AE activity, (b) the same plot with amplitude separation. Black bar on the time scale denote the influence of Cr.EMF; P–stress increment.

Fig. 2 shows the results of measurements of AE from a granite Westerly specimen. This is the temporal dependence of AE activity under uniaxial compression stress of 107 MPa (i.e. 0.85 of the level of the fracture stress by cracking). The background activity of AE was about 1.4 events per second. The stability of the trend (averaged level of AE activity before any external action) was estimated. Fluctuations which occurred before trial loading or interval of $E \times B$ pulses (see Fig. 2) may give rise to 5–8% inaccuracy only for the value of the steady state background level. We undertook the mechanical loading at first. The increment of stress was about 0.4 MPa. The mechanical loading caused the response of AE activity of 120 s duration. Then AE activity relaxed to a new steady level of 3 events per second. Activation of AE due to the pulses of crossed $E \times B$ field began just after the start of the external action. Only 1 min delay was required to achieve the maximal level of AE response in this case. This time the amplitude of electric field was nearly 400 V/m, the frequency–3 kHz. The frequency of the pulses produced by the generator G3-112 (magnetic field) was 6 kHz. The amount of absorbed

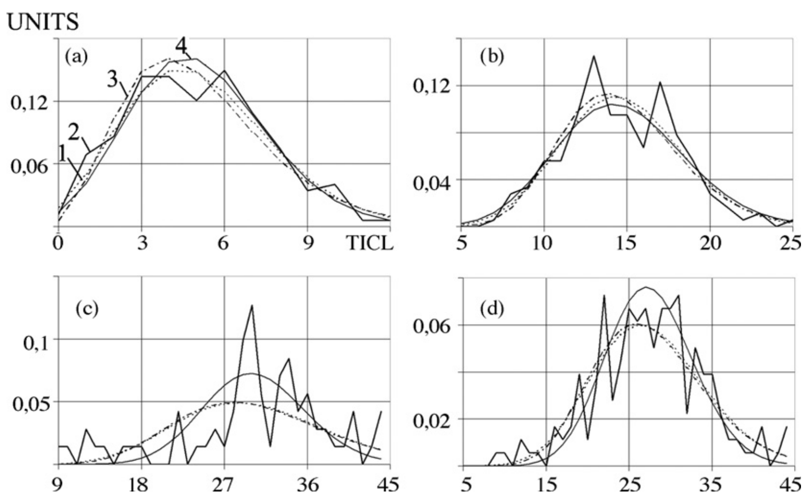

Fig. 3. Plots of distributions of actually recorded events–solid line (2), Poisson distribution–fine line (4), Poya distribution–dashed line (3), gamma distribution–chain line (1). (a) First 15 min in a session, (b) 15 min just before action, (c) first 6 min of action period, (d) all period of action (15 min).

energy due to power influx of crossed $E \times B$ fields was nearly 0.1 J (this estimation is based on the values of the Umov–Poynting vector and of the total duration of all the $E \times B$ pulses, sketched on Fig. 1c). The duration of the AE response was 1765 s.

Fig. 2b demonstrates two temporal dependencies: the grey curve denotes the activity of strong AE signals, and the dark curve the activity of weak AEs. During the extra energy release (AE response) induced by external action the both the curves are practically identical, and the electromagnetic action does not affect the similarity of the trends of the curves. But this is not the case when the main load has been increased and the background level of AE activity has become higher (Fig. 2b). One can see that at the end of the induced activation the number of weak AE signals tends to zero, but the opposite happens with the strong AE signals.

The result denotes that a specimen turns into a new state after the activation induced externally. Meanwhile, the formation of defects with minor length is in progress. The population of minor defects which emitted weak AE signals during the response was likely changed by the external action. The contribution of such defects should drop when the time of additional action is over.

The results of computations of AE events distributions over temporal intervals of chosen length are represented in Fig. 3, separately for periods before, during and after session with additional Cr.EMF. It is evident from Fig. 3a that during a period of usual loading (without action of external fields) the distribution of recorded AEs is in agreement with well-known random distributions. No appreciable change occurs after the increment of the compressive load (Fig. 3b). However, a disagreement between actual distribution of AE events and standard models arises during the first 6 min interval of Cr.EMF action (Fig. 3c). The distribution of AE events in all the 15 min period of additional action becomes again correlated with the modeling of random distributions. We see that the differences between distributions exist only during the initial stage of the action.

4. Summary

The experimental results have demonstrated that the effect of EM fields applied externally is to modify the process of defects accumulation in rocks under near critical loading conditions. The first mode of response manifested itself in numerous experiments with mainly electric impacts. The activation of AE in this mode is likely related to the elastic perturbation due to electric ponderomotive force in heterogeneous media. A threshold of the electrostimulation effect depends on ∇E^2. The second mode of AE simulation effect becomes evident when pulses of Cr.EMF act on specimens under the same strained-stressed state as for first mode. During the second mode the response of AE activity is sensitive to the direction of E and B. This may be associated with linear dependence of threshold on E and B. The presence of two modes put some light on why electric sensitivity of cracking (elastic wave emission) is so different on various spatio-temporal scales.

The analysis of statistical distributions in a flow of AE events denotes another signature of the same defects kinetics and/or straining bifurcation. In the initial time of action of the Cr.EMF pulses the succession of AE events declines from the usual one described by random distributions. According to our previous experiments [16], dissimilar trends of selective activity of strong and weak events were recorded during the initial stage of AE response to mainly electric action. In a given experiment these trends have occurred only after the end of the activation due to Cr.EMF pulses. Nevertheless, a divergence from random distributions has highlighted the initial stage of Cr.EMF action.

The obtained results seem to be relevant to control the relaxation and the inelastic strengthening of solids.

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