Power Characteristics of Electro Burst in Solids

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Abstract – The physical and mathematical model of electro burst in solid is presented. Operation of discharge circuit, discharge channel expansion and propagation of the mechanical stress waves in dielectric materials are self-consistently considered in the model. The model allows to investigate the basic laws of stored energy transfer to the discharge channel and transformation of this energy to wave energy demolishing solid material. Power characteristics of wave disturbances generated by expanding channel in rock depending on the circuit parameters are analyzed for the fracture pattern prediction. Simulation of electro burst dynamics in solids consecutively describes physical processes underlying on electro discharge technologies of solid non-conducting materials processing. The quantitative model of electro burst verified by tests in solids will allow to optimize pulse generator parameters and electrode system constructions of created equipment.

1. Introduction

Electro burst is the fundamental phenomenon of dielectric electro physics, combined with previous electric breakdown determining behavior of materials in strong electric fields. Fracture pattern of solid at electro burst is determined by two major factors: specificity of mechanical stress field formed by extending waves, and extremely nonuniform energy distribution in a wave. Both factors are caused by the small radius of discharge channel ~10^{-4}-10^{-6} m. The small channel radius leads to sharp wave amplitude decrease in a vicinity of discharge channel, caused by wave divergence to radial direction. The radiated by expanding channel shock waves transform to plastic and further in elastic wave with expressed region of tensile tangential stresses [1] which stimulate radial crack nucleation. As wave distribution density of energy in its head part also is sharply reduced. As a result energy infeed of formed cracks mouth becomes worse and hence their number and length are decreased.

2. Electro burst model

The electro technical part of electro burst is described by discharge of capacitor C in the circuit, Fig. 1. The plasma discharge channel was approximated as an expanding cylinder with length l_c and resistance $R_c(t)$ (Fig. 2). When *S* switches on (Fig. 1) solid breakdown occurs (it is not considered in present paper), energy is released within the channel resistance R_c.

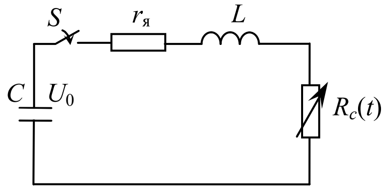
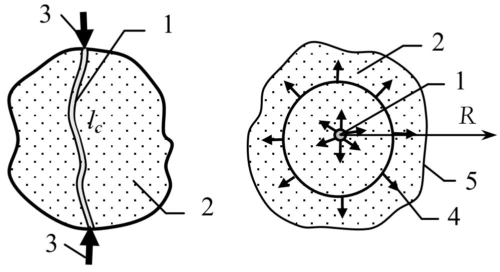


Fig. 1. The electric circuit of the discharge circuit

Channel pressure rises, channel expansion and distribution of stress waves in solid which form a fracture pattern take place. The analysis of wave power characteristics was carried out in material volume with diameter of 4 cm that is greater than dimension of destruction region, up to the wave output on dielectric surface.



a) b)

Fig. 2. Channel disposition after breakdown *(a)*, cross-section area of channel *(b)*, 1 – channel, 2 – solid, 3 – electrodes, 4 – shock wave, 5 – outer solid limit

The scheme of energy transformation without taking power losses on electric breakdown into account (usually ~10 J at cm gaps) is resulted in Fig. 3. Capacitor storage energy is spent on losses in a circuit resistance in part *r* and, basically, allocated in the discharge channel. This part of energy, in turn, is spent on plasma formation and channel expansion work forming a shock wave. Media covered in a wave, is deformed in radial direction and expands. These processes are characterized by deformation energy and kinetic energy of material.

Energy losses caused by the possible plasma outflow from the channel butts were not taken into account in simulation. It is supposed, that the loaded material was continuous, not destroyed in considered time interval. The destroying action prediction of electro burst was carried out on basis of distribution diagram of tangential stress and radial energy distribution in a wave. Thus it was supposed, that solid destruction is caused only by solid deformation energy.

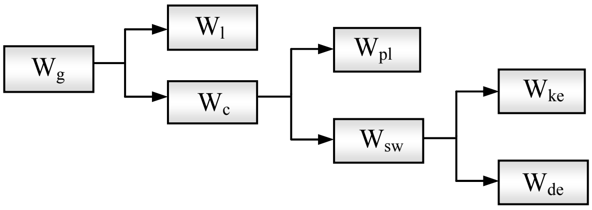


Fig. 3. The scheme of energy transformation. W_g – stored energy, W_l – ohmic losses in circuit, W_c – channel energy, W_{pl} – plasma energy, W_{sw} – wave energy, W_{ke} – kinetic energy of solid in a wave, W_{de} – material deformation energy

The mathematical model includes:

the electro-technical equations of the discharge circuit

$$L\,di/dt + (r_z + R_c)\cdot i = U, dU/dt = -i/C, \quad (1)$$

$$R_c(t) = A_{mid}\cdot l_c / \int_0^t i^2(t)dt, \quad (2)$$

$$W_c(t) = \int_0^t i^2(t)\cdot R_c(t)dt, \quad (3)$$

$$t=0,\ i(0)=0,\ U(0)=U_0, \quad (4)$$

where A_{mid}=611 $V\cdot s^{1/2}m^{-1}$ [2],

the energy balance equation of the discharge channel

$$dW_c = P_c d(\pi r_c^2\cdot l_c) + d(P_c\cdot\pi r_c^2\cdot l_c)/(\gamma-1), \quad (5)$$

where P_c is channel pressure, r_c is channel radius; г is effective ratio of plasma expansion;

the equations of elastic – plastic material pulse deformation [3]:

$$\frac{\partial u}{\partial t} = \frac{1}{\rho_0}\cdot\frac{R}{r}\frac{\partial\sigma_1}{\partial r} + V\cdot\frac{\sigma_1-\sigma_2}{R}, \quad (6)$$

$$\sigma_1 = S_1 - P,\quad \sigma_2 = S_2 - P,\quad \frac{\partial R}{\partial t} = u, \quad (7)$$

$$V = V_0\cdot\frac{R}{r}\cdot\frac{\partial R}{\partial r},\ V = \frac{1}{\rho},\ V_0 = \frac{1}{\rho_0}, \quad (8)$$

$$\frac{\partial e}{\partial t} = -P\frac{\partial V}{\partial t} + V\cdot S_1\cdot\dot{\varepsilon}_1 + V\cdot S_2\cdot\dot{\varepsilon}_2, \quad (9)$$

$$\dot{S}_1 = 2\mu\cdot(\dot{\varepsilon}_1 - \frac{1}{3}\frac{\dot{V}}{V}),\ \dot{S}_2 = 2\mu\cdot(\dot{\varepsilon}_2 - \frac{1}{3}\frac{\dot{V}}{V}), \quad (10)$$

$$\dot{\varepsilon}_1 = \frac{\partial u}{\partial R},\quad \dot{\varepsilon}_2 = \frac{u}{R}, \quad (11)$$

where r and R are initial and current coordinates of dielectric elements, c, c_0, P, u, y_i, S_i, $\dot{\varepsilon}_i$, e are current and initial density of solid, pressure, mass speed, tensions, components of tension deviator, components of the deformation speed tensor, internal energy of material mass unit, м is the modulus of solid elasticity in shear.

For fluidity calculation the low of Mizes's fluidity was used [3].

As the model material the granite with a percussive adiabat is chosen

$$P = \rho_0 c_l^2(\rho/\rho_0 - 1)(\rho/\rho_0)^n, \quad (12)$$

where c_0=2.67 g/cm^3, c_l =5850 m/s is the elastic wave speed, n=2 is the constant characterizing material, м = 31.6·10^9 Pa, Y=0.25·10^9 Pa is the Jung's module.

Deformation energy and kinetic energy were calculated as:

$$W_{de} = 2\pi l_c\cdot\int_{r_c}^{r_w} e\rho R dR,\quad W_{ke} = \pi l_c\cdot\int_{r_c}^{r_w} u^2\rho R dR,$$

$$W_{sw} = 2\pi l_c\int_0^t P_c r_c dr_c = W_{de} + W_{ke}, \quad (13)$$

where r_w is the radius of solid area covered with extending wave.

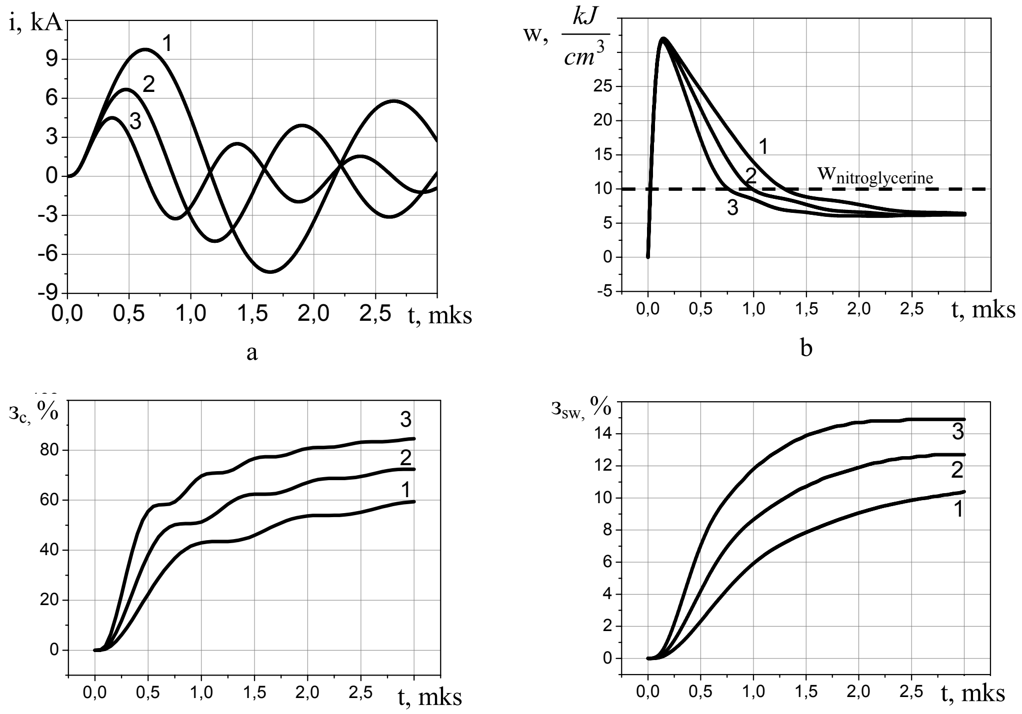
The resulted equations were integrated numerically [3] with zero initial conditions t=0: R=r, $U(r)$=0, c(r)=c_0, $y_i(r)$=0, $e(r)$=0 for r>r_c=r_0 and boundary condition as $P_c(t)$.

The initial channel radius was 5 microns. For liquid and solid materials г according to [4, 5, 6] changes in a range 1,25...1,05. In simulation г was equal to some average value 1,1 [6]. The circuit parameters were changed in ranges C=5…20 nF, U_0=250…350 kV, L=10…25 mkH, r_z =1 Ohm. The channel length was l_c=0,5…2 cm.

3. Simulation results

Typical dependences of energy transformation for three discharge regimes (typical parameters for electro discharge technologies), are shown in Fig. 4 where the following designations are accepted: $W_g = CU_0^2/2$, specific channel energy $w = W_c/\pi r_c^2 l_c$, coefficients of energy transformation to the channel $\eta_c = W_c/W_g$ and wave energy $\eta_{sw} = W_{sw}/W_g$.

The analysis of received dependences shows, that the main stage of tension wave formation in solid finishes by the end of first half-period $T_{0,5}$ of the discharge current $t\sim\pi\sqrt{LC}$. The second and the subsequent current pulsations almost are not influenced on the wave energy. It is caused by two reasons. First, efficiency of energy transformation to the wave energy did not exceed 15 % in considered regimes. Second, the discharge channel can be a source of pulse loading only at the initial stage of the discharge (during $t\sim\pi\sqrt{LC}$). It follows from Fig. 4 *(b)* where the volumetric density of energy in the discharge channel is compared with the nitroglycerine volumetric density of energy (a stroke-line) [6].



a

b

c

d

Fig. 4. Time dependences of current *i (a)*, volumetric density of energy *w (b)*, coefficients of energy transformation to the channel energy $з_c$ (*c*) and to the wave energy $з_{sw}$ (*d*) at U_0=200 kV, *L*=5 mkH, *C*, nF: 1 – 20, 2 – 10, 3 – 5

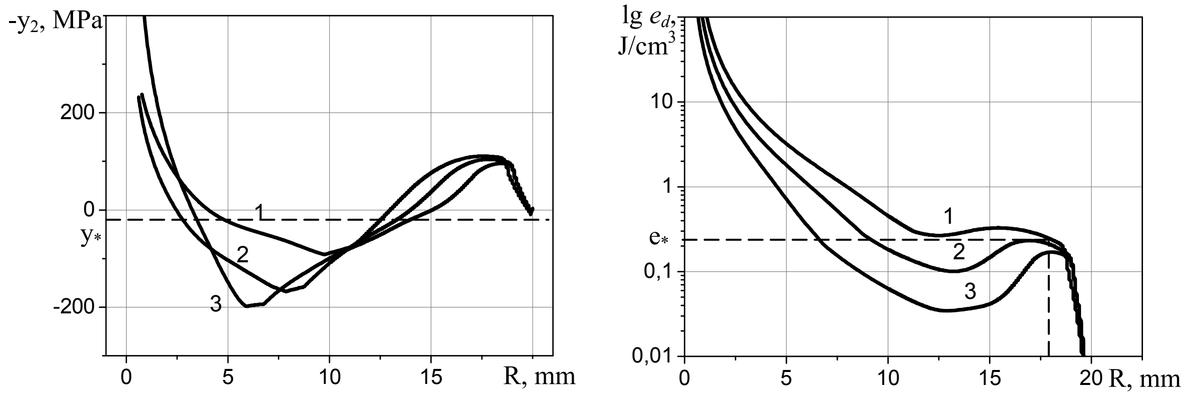
In this time the channel expands intensively and generates shock wave in solid. Further the channel volume rises, the volumetric density of energy is considerably reduced and, accordingly, expanding channel does not generate waves. In this connection additional energy input to the second and the subsequent current pulsations is less effective with the purpose of increase of the wave energy. In Fig. 4 (*c*, *d*) change of two main parameters $з_c$ and $з_{sw}$, determining efficiency of energy transformation to the channel and shock wave is shown. As shown in Fig. 4 during the first half-period of current the basic part of energy W_g is input. Consequently the wave is formed mainly in this time period.

Comparison of received dependences shows, that increase in generator capacity results in growth of absolute values W_c and W_{sw} but their relative values $з_c$ and $з_{sw}$ are decreased. This dependence is caused by less rapid growth W_c and W_{sw} in respect of W_g.

Corresponding tangential stress distribution diagrams in solid and radial distributions of deformation energy concentration in a wave are shown in Fig. 5. Value $e_d(R)$ shows the quantity of volume. Tangential stress distribution diagrams y_2 show, that region of tensile stress is formed in the wave in which tensile stress exceeds a granite tensile strength y_* =8 MPa [7]. It means that in the considered range of generator energy change and discharge gap parameters in solid there will be conditions for radial crack initiation and germination, and material destruction. Crack number and crack length are basically determined by energy distribution in a wave. Fig. 5, b (a curve 1) shows, that the greatest deformation energy concentration there is in a vicinity of the channel. In the area ($r_c < R \le 2{,}5$ mm) compression stress and energy concentration are sufficient for solid crush. As the distance from channel decreases the volumetric density of energy is reduced. And for $R \ge R_* \approx 18$ mm (Fig. 5, b, a curve 1) energy concentration in solid, according to [8] becomes less than density of effective destruction e_*. Hence, energy inflow to a crack mouth will be insufficient, and crack propagation caused by direct wave, on this distance from channel will be stopped. In the area of $2{,}5 \le R \le R_*$ depending on ratio $n = e_d / e_*$ germination *n* cracks is possible. Comparison of distributions y_2 and e_d also shows, that the area of tensile tangential stress in solid is formed earlier with reduction of pulse energy, but corresponding wave power characteristics become less than density of effective destruction energy e_* (Fig. 5, b, curves 2, 3). It means, that conditions for crack nucleation are realized at rather small power input to discharge channel, but the wave energy is insufficient for propagation of extended crack network. Simulation results are in a good agreement with experimental data [9].

4. Conclusion

As a result of executed research the physical and mathematical model of electro burst in condensed dielectrics, including stress and power criteria of material destruction is presented. The model adequately describes transformation of storage energy to energy of wave disturbances, resulting to solid destruction. On the basis of tangential stress diagrams and distribution of wave energy density conditions of radial cracks nucleation and propagation are analyzed, allowing to predict a solid fracture pattern.



a b

Fig. 5. Tangential stress distribution diagrams y_2 *(a)* and radial distribution of energy concentration e_d *(b)* in a wave at t=3 mks, U_0=200 kV, L=10 mkH, C, nF: 1 – 20, 2 – 10, 3 – 5

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