Electro Discharge Demolition of Concrete Blocks with Breakdown Initiation by Exploding Wire

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Abstract – Results of experimental and theoretical investigations of electro discharge demolition of concrete blocks with breakdown initiation by exploding wire have been presented. Metallic wire usage has been enabled to decrease the operating voltage of generator, to increase the discharge gap length and hence, the channel energy that has been leaded to the demolition build-up at electroburst. Dynamics of electrical energy transformation to the wave energy and stress field formation have been considered.

1. Introduction

One of the ways of electrical breakdown initiation of condensed materials in electro discharge technologies of treatment and demolition is the wire electroburst (exploding wire). Wire electroburst is the fast process of wire expansion at heating by the current of big density (up to $10^{12}$ A/m$^2$), its destruction which is accompanied by shock wave generation and propagation in the surrounding material [1]. The material adjacent to the wire is the medium which transfer the pressure. The shock-wave disturbances generated by the wire electroburst and following expansion of the discharge channel in different media are widely used in technics and technologies due to possibility to control their parameters in the wide range by variation as parameters of the discharge $R–L–C$ circuit and the sizes and material of bursting wire [1–3]. Metal vapor at such method of breakdown initiation allow to decrease the operating voltage of technological installations.

The amplitude and energy of radiated wave at electroburst are determined basically by three inter-connected groups of parameters: discharge circuit parameters of pulse generator, the wire length and its material and physical-mechanical properties of the surrounding material. Evaluation of the complex of the above-mentioned parameters providing the required wave pressure characteristics is one of the major tasks of electro discharge technologies.

In this paper by means of the developed physical and mathematical model the power characteristics and shock-wave propagation are investigated at the copper wire electroburst in condensed media polyethylene–concrete depending on the length and diameter of the exploding wire.

It has been found experimentally that the closer mode of energy release in the discharge channel to the critical mode when $R = \frac{2L}{\sqrt{C}}$ (here $R$ is the total resistance of the channel and spark of the switch) the more electrical energy release in the discharge gap. Change of value $R$ is possible due to change of the length $l_{ch}$ and diameter $d_{ch}$ of the exploding wire. Thus it is possible to increase not only the energy allocated in the channel but also the energy of wave destroying the solid, without variation of pulse generator parameters. However increase in $l_{ch}$ and $d_{ch}$ result in expenditure of the energy for the wire heating and its burst that leads to the reduction of the energy-conversion efficiency to the wave energy and as a result to degradation of solid destruction. Thus, it is necessary to carry out the complex analysis of power characteristics of the wave disturbances generated by the expanding channel, and the wave dynamics of tensely-deformed solid state for fracture pattern prediction.

Effectiveness of application of materials with higher acoustic stiffness in comparison with water as the transfer medium for increasing the efficiency of electrical energy conversion to the wave energy, which destruct the material has been shown in [4, 5]. Application of polythene allows to increase the wave energy by ~20–25% in comparison with the electrical discharge in water. Thus the pressure amplitude of generated wave increases for ~25–30% [4]. The choice of polythene as the material surrounding the wire is caused also by absence of crush zone in a vicinity of the channel that allows to avoid considerable expenditure of energy in this zone. For verification of simulation results experimental investigations of electroburst in concrete blocks were carried out with initiation of the electrical breakdown by the exploding copper wire in an electroexplosive cartridge.

2. Scheme of electro discharge demolition and the basic equations

The pulse generator operation has been analyzed at its discharge on the discharge gap which is short-circuited by the copper wire placed in the polyethylene cartridge. The cartridge was placed in a drilled hole in the concrete block. During the discharge the

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wire explosion and plasma channel formation occur, expanding channel generates the pressure wave which propagate in a polyethylene cartridge and then in solid. The wave, being propagated, refracts in part in concrete and reflects in polythene, then turns back to the channel and react upon it (Fig. 1). As a result in the system of materials polythene – concrete intricate profile and dynamically changing wave pattern are formed which result in deformations and material demolation.

![Image](image-url)

**Fig. 1. Scheme of solid electro discharge demolition:** 1 – coaxial cable; 2 – electro discharge cartridge (copper wire in polyethylene); 3 – shock-wave disturbances, generated by the expanding channel; 4 – concrete block.

The physical and mathematical model includes the consistent solution of the electro-technical equations for the discharge circuit (Fig. 1), the energy balance equation of the channel, hydrodynamical equations for description of wave disturbances and state equations for wire, plasma channel and surrounding medium [6]. Time dependences of discharge current and voltage have been calculated according to the Kirchhoff’s equations along with the empirical equations for resistances of copper wire and plasma channel. The resistance of the discharge channel before wire explosion on each time step is determined as [2]:

\[
R_{ch}(t) = R_{a0}(1 + 68.065 \frac{W}{W_{ch}} - 233.188 \left(\frac{W}{W_s}\right)^2 + 1526.428 \left(\frac{W}{W_s}\right)^3 - 57.867 \left(\frac{W}{W_s}\right)^4)
\]

(1)

where \(R_{a0}\) is the initial resistance, \(W\) is the specific energy of the copper wire. The initial resistance is defined as

\[
R_{a0} = l_{ch} \frac{1}{s} \rho_{cop}.
\]

(2)

Here \(l_{ch}\) is the wire length, \(s\) is the wire cross section area, and \(\rho_{cop}\) is the specific resistance of copper. Specific energy of the copper wire is defined as follows:

\[
w = \frac{1}{m} \int_{0}^{t} R_{ch} dt,
\]

(3)

where \(m\) is the mass of wire.

At \(t < t_{ex}\) (where \(t_{ex}\) is the wire explosion time moment) the material surrounding the wire was considered undisturbed. At \(t \geq t_{ex}\) the energy released in the plasma channel \(W_{ch} = \int_{0}^{t} R_{ch}(t) dt\) according to the energy balance equation \(W_{ch} = W_{pl} + W_w\) was spend for the plasma formation \(W_{pl} = P_{ch}V_{ch}/(\gamma - 1)\) and work of the channel expansion \(W_w = P_{ch}dV_{ch}\) forming a shock wave in the solid, where \(P_{ch}\) is channel pressure and \(V_{ch}\) is its volume, \(\gamma = 1.1\) [7].

The breakdown channel resistance \(R_{ch}(t)\) after wire explosion is determined through the integral of current action in form of Vaicel–Rompe [8]:

\[
R_{ch}(t) = \frac{A_{mid} - l_{ch}}{\int_{0}^{t} R_{ch} dt},
\]

(4)

where \(A_{mid}\) is the a spark constant (in case of polyethylene \(A_{mid} = 210 \text{ V} \cdot \text{s}^{3/2} \cdot \text{m}^{-1}\) [7]).

Wave distribution has been described in hydrodynamical approximation with cylindrical symmetry. Polythene compressibility has been described by the state equation in the form of shock adiabat \(D = a + bU\), where \(D\) is the shock wave velocity; \(U\) is the mass speed at the wave front. This equation by means of Rankine–Hugoniots equations [9] was transformed into

\[
P = \rho_o a^2 \left[1 - \frac{\rho_o}{\rho}\right] \left[1 - b \left(1 - \frac{\rho_o}{\rho}\right)^{2}\right],
\]

(2)

where \(P\) is the pressure in material covered with a wave; \(\rho_o, \rho\) are the initial and current material density. For polyethylene \(\rho_o = 0.94 \text{ g/cm}^3\), \(a = 2901 \text{ m/s}\), \(b = 1.481\) [9].

3. Experimental and simulation results

Pulse generator parameters are: \(C=96 \mu\text{F}\), circuit inductance \(L = 1.169 \mu\text{H}\), charging voltage \(U_{0} = 15 \text{kV}\), ohmic circuit resistance \(r_s = 0.022\ \text{Ohm}\). Parameters \(L\) and \(r_s\) have been determined from the short-circuit test. Parameters of copper wire initiating the discharge have been varied within: \(l_{ch} = 20...50\ \text{mm}\), diameter \(d_{ch} = 0.17...0.7\ \text{mm}\). Diameters of the drilled hole and polyethylene cartridge were \(24\ \text{mm}\), the hole depth \(14\ \text{cm}\), the hole was drilled on the distance \(15\ \text{cm}\) from the concrete block surface. The block parameters: \(A = 150\ \text{mm}\), \(B = 170\ \text{mm}\), \(H = 150\ \text{mm}\) (Fig. 1).

Time dependences of experimental discharge current at different length of exploding wire are shown in Fig. 2.

The burst time in all cases are mainly the same and makes \(t_{ex} = 3.7\ \mu\text{s}\). The difference between calculated \(t_{ex}\) and measured experimentally does not exceed 7%. The model verification was carried out by comparison of calculation and experimental current, Fig. 3. The accuracy of calculation makes less than 5%.
The energy for the wire explosion makes up \( \sim 1-2.5\% \) from \( W_g \). An enhancement of the wire length \( l_{\text{ch}} \) results to the increasing of energy allocated in the channel and wave energy \( W_w \), radiated in solid (Fig. 4). At the same time \( W_w \) makes up from \( \sim 2 \) up to \( 5\% \) from the stored energy. The maximal density of energy developed in the channel in the first quarter of a half-period current oscillation reaches \( \sim 60 \text{ kJ/cm}^3 \).

The energy input into the plasma channel leads to the channel pressure buildup that results in plasma expansion. The expanding channel generates plastic-elastic waves into the material. The wave characteristics essentially depend on the variation of channel pressure. The fracture pattern of material is determined by the resulting tensely-deformed solid state, generated at interaction of direct and reflected waves. Radial \( (\sigma_1) \) and tangential \( (\sigma_2) \) mechanical stress distribution in concrete at time moment 120 \( \mu \text{s} \) are shown in Fig. 5. The figure shows that stress distribution diagrams are of intricate profile formed by superposition of direct and reflected waves. It is necessary to note, that the level of wave stresses is rather low and is in the range of elastic deformation of material. A region of tensile tangential stresses is formed in the wave propagating in concrete (Fig. 5, b).

Formation of this region results in the radial crack nucleation and growth which propagate from a hole wall to the surface of concrete block, Fig. 6. It is noticeable, that in the considered case the radial stresses \( \sigma_1 \) are compressive in point time interval. This situation does not stimulate the development of the concentric cracks which are typical for chemical explosion. At such wave parameters germination only several main cracks is possible as in the case of experiment. As it is shown in Fig. 6, b reduction of wire length leads to an enhancement of zone of tensile tangential stress that results in growth of probability of radial cracks generation.
Variation of diameter of an initiating wire is not so effective for solid demolition as in case of changing wire length due to the greater power consumption \( W_{ex} \) for the wire explosion: for \( d_{wh} = 0.17, 0.37, 0.7 \text{ mm} \)
\( W_{ex} = 70.2, 117, 355 \text{ J} \) respectively, thus the time of wire explosion \( t_{ex} \) makes up 1.02, 2...67, 6.47 μs.

4. Conclusion

Efficiency of wire application for initiation of the discharge at electroburst destruction of concrete blocks is shown. It is possible to provide the optimal mode of channel expansion as a source of pulse loading by the choice of the wire length matched with the parameters of the discharge circuit of generator. Results of researches have been shown, that efficiency of solid demolition increases with growth of the wire length.

The calculated stress field and the executed prediction of a fracture pattern are in good agreement with the experiment results.

References