Effect of electro-discharge circuit parameters on the destructive action of plasma channel in solid media

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Abstract. The results of computer blast-hole experiments with copper wire electro-explosion in the polyethylene-concrete media has been analyzed with shock and pressure wave dynamics depending on the spatiotemporal distribution of electrical power deposition in plasma channel. Pressure and stress-wave dynamics of tensely-deformed material state has been analysed by means of physical and mathematical model, which consistently describes the operation of the discharge circuit, plasma channel expansion, generation and propagation of the shock and pressure waves in the condensed media. It has been shown the significant dependence of the stress-wave profile on the pressure pulse wave shape on the borehole wall which is determined by the rate of electrical energy release in the plasma channel and is weakly depended on the time of energy release (at given rate of its release). Analysis of stress-wave dynamics have been shown that the rapid power deposition results to the higher amplitude of compressive stresses in the wave. The lower energy deposition rate in plasma channel leads to the higher amplitude of tensile stresses both in radial and tangential direction.

1. Introduction
Over the past decade, electrically produced shocks in condensed media have been used as the means of rock/concrete fragmentation, drilling and destruction [1–6]. Most of such experiments normally involve producing an electrical discharge in a water-filled cavity drilled in the rock. One of the ways of the plasma discharge channel initiation in the condensed materials is the wire electro-explosion. Shock-wave disturbances launched from the expanding discharge plasma channel initiated by electrical wire explosion in different media are widely used in engineering and electro-discharge technologies due to possibility to manage their characteristics in a wide range by varying parameters of the discharge RLC-circuit, and the size and material of explosion wire [7-10].

A high voltage pulsed power electric discharge through a solid can create a plasma channel of high energy density of about 25-30 kJ/cm³ [10]. Inside the channel the electric energy is transformed into internal thermodynamic energy which subsequently is used to deform and finally destruct the surrounding solid. This process is the basis for many technological applications where typically 10-100 J/cm of energy are deposited from a high voltage pulse generator in less than a few µs, leading to the plasma channel temperatures around 10⁴ K and pressures of up to 10⁹ Pa. The plasma channel, initially only ~10 to 50 µm wide, expands and launches a pressure wave into surrounding solid material causes the tensely-deformed material state and formation of the mechanical compressive, tensile and shear stresses. Mechanical stresses are in the range of tens to hundreds of MPa and cause the solid to be destructed. This effect is comparable to that of a chemical explosion in a preformed...
borehole. However there are few distinctive features: in an electro-explosion the relative radial expansion of the plasma channel is a factor of $10^{-10^3}$ larger and its temperature is a factor of 10 higher. Also the quantity and energy release rate can be controlled over a much broader range by varying the time of electrical energy release from a few to hundreds of microseconds.

The destructive effect of the surrounding solid material depends on the pressure versus time waveform, $P_g(t)$, produced on the walls of the borehole. This pressure, in turn, depends on the spatiotemporal distribution of electrical power deposition (electrical energy release rate) in the plasma channel, and on shock wave propagation through the media. Thus the amplitude and profile of generated pressure wave causing the material destruction are basically determined by the power of energy release in the channel and the expanding wave energy. The main goal in raising the efficiency of electro-discharge technologies is therefore matching of energy release rate conditions during the discharge and characteristics of the generated pressure wave.

The lack of experimental information about the general laws determining the amplitude and profile of the pressure wave generated by the plasma channel expansion in the condensed media does not allow estimation of the generated pressure in the surrounding material according to the measured electrical discharge characteristics (current and voltage). Some attempts have been made in case of the discharge in liquids by the authors of monographs [8, 9], but formulation of their practical problems did not assume the recording of the shock wave profile. The analysis of the examined processes, an understanding of shock wave propagation is thus essential for improvement of electro-discharge technologies, optimizing pulse generator parameters and the discharge modes coordinated with the wave dynamics in the destructible material and conditions of its destruction. The objective of this work is to develop physical insight into shock wave generation and propagation in condensed media at electrical discharge. To solve this problem a physical and mathematical model has been presented, which consistently describes the operation of the discharge circuit, plasma channel expansion, generation and propagation of the shock and pressure waves in the condensed media. In our research, the copper wire electro-explosion in the polyethylene-concrete media has been analyzed with shock and pressure wave dynamics depending on the spatiotemporal distribution of electrical power deposition in plasma channel.

2. Numerical physics-based research method of shock and pressure wave dynamics and solid destruction

The electric circuit diagram of the pulse generator that was used in experiments and simulation is shown in figure 1.

![Figure 1. Scheme of plasma-blasting fracture of concrete: 1 – coaxial cable; 2 – electro-blast cartridge; 3 – shock-wave disturbances, generated by expanding plasma channel; 4 – concrete test specimen.](image)

It was shown in [11] that for increasing the efficiency of electrical energy conversion into the pressure wave energy, the amplitude of shock wave and efficiency of its transfer to the destructible material the polyethylene cartridge with copper wire in its center line was used. The cartridge was placed in a drilled hole in the concrete sample. During the discharge the wire explosion and plasma
channel formation occurs. After the electrode gap bridging by plasma channel the energy accumulated into the capacitor bank of the power supply $C$ is released into it. Resistance $r$ and inductance $L$ are the stray parameters of the circuit. Joule heating of the plasma channel results in extremely rapid channel pressure buildup and subsequent plasma expansion. A steep pressure rise takes place on the walls of the hole, generating a shock wave in the surrounding material. The propagation of shock and pressure wave disturbances forms tensely-deformed solid state and results to the mechanical compressive, tensile and shear stresses which are in the range of tens to hundreds of MPa and therefore cause its further destruction. An enhancement of mechanical fracture work (pressure wave energy) produced by the plasma channel is the main goal of energy optimization.

The physical and mathematical model of investigated system consist of equations describing the wave conversion of electrical energy, shock-wave effects and dynamics of deformed solid material.

Electrodynamic oscillating processes in the discharge circuit were characterized by the voltage balance equation:

$$L \frac{di(t)}{dt} + (R_{ch} + r)i(t) + \frac{1}{C} \int_0^t i(t') dt' = U_0,$$  

(1)

where $L$ is the circuit inductance, $\mu$H; $R_{ch}$ is channel resistance, $\Omega$; $i(t)$ is the current in the circuit, $A$; $U_0$ is the charge voltage of capacitor bank, $V$; $r$ – active resistance of the generator, $\Omega$.

Electrical plasma channel energy conversion into the plasma energy and mechanical work, performed by expanding channel:

$$\frac{1}{\gamma-1} \frac{d}{dt} (P_{ch} V_{ch}) + P_{ch} \frac{dv_{ch}}{dt} = i(t)^2 R_{ch},$$  

(2)

where $\gamma$ is the effective ratio of specific heats; $P_{ch}$ is the channel pressure, Pa; $V_{ch} = \pi r_{ch}^2 l_{ch}$ – channel volume, $m^3$; $r_{ch}$ and $l_{ch}$ are the channel radius and length accordingly, $m$.

Dynamics of shock and pressure waves in polyethylene and concrete was described with the hydrodynamical equations in the form of equations of conservation of momentum, mass, and energy in the Lagrangean coordinates for cylindrical symmetry [13, 14, 10].

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 [8]:

$$R_{ch}(t) = R_{ch0}(1 + 68.065 \frac{W}{W_s} - 233.188 \left( \frac{W}{W_s} \right)^2 + 1526.428 \left( \frac{W}{W_s} \right)^3 - 57.867 \left( \frac{W}{W_s} \right)^4),$$  

(3)

where $R_{ch0}$ is the initial resistance, $w$ is specific energy of the copper wire. The initial resistance is defined as

$$R_{ch0} = \frac{l_{ch}}{s} \rho_{cop},$$  

(4)

Here $s$ is the wire cross section area and $\rho_{cop}$ is specific resistance of copper. Specific energy of the copper wire is defined as follows:

$$w = \frac{1}{m} \int_0^t i^2 \cdot R_{ch} \cdot dt,$$  

(5)

where $m$ is mass of wire.

The breakdown channel resistance $R_{ch}(t)$ after wire explosion is determined through the integral of current action in form of Vaicel-Rompe [12]:

$$R_{ch}(t) = K_{ch} \cdot l_{ch} \left( \int_0^t i^2(t) dt \right)^{-\frac{1}{2}},$$  

(6)

where $K_{ch}$ is a spark constant (in case of polyethylene $K_{ch}=210 \text{ V} \cdot \text{s}^{0.5} \cdot \text{m}^{-1} [5]$).

Polythene compressibility has been described by the state equation in the form of shock adiabat $D = a + b U$, where $D$ – shock wave velocity, $U$ – mass speed at the wave front. This equation by means of Rankine-Hugoniot equations [15] was transformed into:
\[ P = \rho_0 a^2 \left( 1 - \frac{\rho_0}{\rho} \right) \left[ 1 - b \left( 1 - \frac{\rho_0}{\rho} \right) \right]^2 \]  \hspace{1cm} (7)

where \( P \) – pressure in material covered with a wave, \( \rho_0, \rho \) – initial and current material density. For polyethylene \( \rho_0 = 0.94 \text{ g/cm}^3 \), \( a = 2901 \text{ m/s}, b = 1.481 \) [15].

3. Simulation results
Several plasma blasting computer simulation scenarios were run and examined on concrete with diameter of the drilled hole of 26 mm and its depth of about 300 mm. The hall was drilled in the distance of 300 mm from the concrete block surface. The length and diameter of copper wire initiating the discharge were 100 mm and 0.27 mm, respectively. For instance three values of electrical energy release rate were chosen in the experiments: \( U_0 = 13 \text{ kV}, L = 1.22 \text{ µH}, C_1 = 560 \text{ µF}, C_2 = 840 \text{ µF}, C_3 = 1120 \text{ µF} \).

The distractive effect of concrete is determined by the maximal pressure developed in the plasma channel, shock and pressure wave energy, and the field of tensile mechanical stresses. As a result of Joule energy-release in plasma channel its internal energy and conductivity raise, which leads to the increase in the current amplitude. Positive feedback between the heat build-up and conductivity causes an increase in the internal energy of plasma channel (figure 2, a). The electrical power deposition reaches \((6–8) \times 10^5 \text{ W} \) (figure 2, b).

![Figure 2](image_url)

**Figure 2.** Channel (\( W_{\text{ch}} \)), pressure wave (\( W_{\text{w}} \)) energy (a) and electrical power deposition (b) versus time for different pulse generator capacitance.

Explosive electrical energy release in plasma channel leads to a sharp increase in the channel pressure up to 5.5 GPa, leading to its expansion (figure 3). The channel pressure is not substantially stabled; the increase in the channel volume causes the pressure reduction and consequently the slowdown of its expansion. The speed of pressure reduction depends on the dynamics of electrical power deposition in the channel. The time-history of the pressure pulse, produced on the borehole walls versus electrical energy release rate is shown in figure 4.
The expanding plasma channel generates shock waves. The geometrical divergence and dispersion result in shock wave damping along the way of its propagation. In the vicinity of the channel the shock wave transforms into the mechanical stress-waves propagating in combination of polyethylene–concrete materials. The stress-wave profile essentially depends on the pressure pulse wave shape on the borehole wall, which in its turn is determined by the rate of electrical energy release in the plasma channel. Figure 5 illustrates the radial and tangential stress profiles at time lying near the peak in the power level (see figure 2 (b)). It is clear from figures 4 and 5 that rapid power deposition result to the higher amplitude of compressive stresses.

The fracture pattern of solid is determined by the resulting tensely-deformed solid state, generated at interaction of direct and reflected waves. Dynamics of radial and tangential mechanical stress distribution in concrete after the wave reflection is shown in figure 6. It shows that stress distribution diagrams are of intricate profile formed both by direct and reflected waves.

The necessary condition for the crack initiation in concrete is presence of the region of tensile stresses both in radial and tangential directions. The crack was initiated when one of the stress components has exceeded the tensile strength of concrete, which is about (5–10) MPa according to the literature. Wave dynamics in figures 5 and 6 shows that the lower energy deposition rate leads to the higher amplitude of tensile stresses both in radial and tangential direction. By contrast, in the rapid deposition case the region of tensile stresses in the wave is formed later. Efficiency of generator energy transmission to the wave energy for different rates of energy release is about 22 %, 20 % and 19 % respectively.
Figure 6. Distribution diagrams of radial (a) and tangential (b) stresses in concrete after the wave reflection from the concrete surface at time of 160 mks.

Thereby, the results of plasma blasting computer simulations have shown that the rapid power deposition produces an increase in peak pressure on the borehole wall. However, because it is produced by a shock, pressure on the borehole walls, falls off rapidly, whereas slow deposition produces sufficiently sustained pressure pulse.

4. Conclusion
Results of computer experiments demonstrate the necessity for complex analysis of the electrical energy balance in electrical discharge system from the pulse generator to the pressure and stress wave energy. It is shown the significant dependence of the stress-wave profile on the pressure pulse wave shape on the borehole wall which, in its turn, is determined by the rate of electrical energy release in the plasma channel and is weakly dependent on the time of energy release (at given rate of its release). Analysis of stress-wave dynamics have been shown that the rapid power deposition results to the higher amplitude of compressive stresses in the wave. The lower energy deposition rate in plasma channel leads to the higher amplitude of tensile stresses both in radial and tangential direction. By contrast, in the rapid deposition case the region of tensile stresses in the wave is formed later.

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