IOP Conf. Series: Journal of Physics: Conf. Series **830** (2017) 012043 doi:10.1088/1742-6596/830/1/012043

Characteristics of capillary discharge channel and its effect on concrete splitting-off by electro-blasting method

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Abstract. The numerical simulation results on fracture of a concrete block due to dynamic explosive loads applied to the walls of a blast hole are presented. The influence of the pulse shape on the shock-wave dynamics is considered. A comparison of mechanical stresses in direct and reflected pressure waves induced in the concrete block by explosion pulses of various durations and amplitudes shows that the shorter pulses with higher amplitudes and steeper rise times provide a higher blasting efficiency. The wire application for the discharge initiation enables the operating voltage of the generator to decrease, the discharge gap to increase, and hence, the channel energy to lead to the demolition build-up at electro burst. The significant dependence of the stress-wave profile on the pressure pulse wave shape at the borehole wall, which is determined by the rate of electrical energy release in the plasma channel, has been shown. An analysis of the stress-wave dynamics has shown that the rapid power deposition into a plasma channel tends to shift an amplitude of the tangential stresses in a reflected wave to the higher values and to extend the region of tensile tangential stresses initiating the main crack propagation from the borehole walls to a free material surface.

1. Introduction

Research of the electro-blasting destruction and the splitting-off of solid materials, due to intensive development of the electro-discharge technologies, is of great theoretical and practical interest. Practical interest is provided with the development of technologies of solid processing and destruction by the use of electrical discharge and its advantage over the mechanical methods. The main advantages are as follows: the impulse loading of the material, providing the brittle material fracture with a predominance of tensile and shear stresses and, hence, the destruction at lower mechanical stresses compared to the destruction using compression, like in the mechanical methods.

Thus, the electro-discharge technologies of material processing and the destruction are energy efficient, since the solid destruction occurs mainly due to the tensile and shear stresses, rather than compressive ones, as in mechanical methods. Accordingly, the specific energy consumption is reduced proportionally to the ratio of material strength, by 2-5 times. The pulse loading provides a brittle solid fracture with minimal energy loss for the plastic deformation.

High energy density of the plasma channel (of about 25-30 kJ/cm^3 [1]) allows creation of the conditions for the crack initiation in a solid at relatively low values of a single pulse energy, which is equivalent to grams of trotyl. The possibility of regulation over a wide range of the mode of channel energy release allows the creation of the optimal conditions for solid loading, crack propagation, and material destruction depending on the kind and size of the destructible solid.

The efficiency of electro-discharge method, in comparison with the traditional mechanical ones, strongly depends on the electrical properties of the destructible material and almost does not depend on its mechanical properties, and with increasing of the rock strength, it increases. Therefore, although the method can be applied to materials of a various mechanical strength, the greatest technical and economic effect of its application is reached for hard rocks and materials, which is a priority area of its use.

The expanding conducing plasma channel of a capillary discharge is a promising physical tool for the electro discharge technologies of a solid fragmentation, boring, cutting, a surface cleaning, and others [2–5]. Most of such experiments normally involve an electrical discharge in a water-filled cavity drilled in the rock. One of the ways of the plasma channel initiation in the condensed materials is the wire electro-explosion. The plasma channel, initially only 10 to 50 μm wide, expands and launches a pressure wave into the surrounding solid material causing the tensely-deformed material state and forming the mechanical compressive, tensile, and shear stresses. The mechanical stresses are in the range of hundreds of MPa and cause the solid material destruction. This effect is comparable to that of a chemical explosion in a preformed borehole.

A fracture pattern of the surrounding solid material depends on a pressure profile Pg(t), produced at the borehole wall. This pressure, in turn, depends on the spatiotemporal distribution of electrical power deposition in the discharge channel, and on the dynamics of shock-wave propagation through the material. The main goal in raising the efficiency of electro-discharge technology is therefore matching of the rate of electrical energy deposition with the profiles of the generated shock waves.

The absence of experimental information about the general laws determining the amplitude and profile of the pressure waves launched by the plasma channel expansion in the condensed media does not allow estimation of the generated pressure in the surrounding media according to the measured electrical discharge characteristics (the current and the voltage). Some attempts have been made for the discharge in liquids by the authors of monographs [6, 7], but their formulation of practical problems did not assume recording of the shock wave profile. The analysis of the shock-wave processes, the understanding of mechanisms of the shock wave propagation are, thus, essential for an improvement of the electro-discharge technologies, optimizing the pulse generator parameters and the discharge modes coordinated with the wave dynamics in the destructible material. The eventual aim of this research is to develop the physical insight into the shock wave dynamics in condensed media under the capillary electrical discharge. To progress towards it, the present work has focused on the simulation of computer blast-hole experiments with copper wire electro-explosion in the combination of materials "polyethylene – concrete" and an analysis of the shock and pressure wave dynamics, depending on the rate of electrical energy release in the channel.

2. Numerical electro-blast model

For revealing the basic laws of the energy realize to the discharge gap and transformation of a part of this energy to a shock-wave resulting in solid material destruction, the mathematical model of electro-blast in solid has been developed. The model consistently describes the operation of the discharge circuit of pulse generator, the plasma channel expansion, the generation and propagation of the shock and pressure waves in the polyethylene and concrete.

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

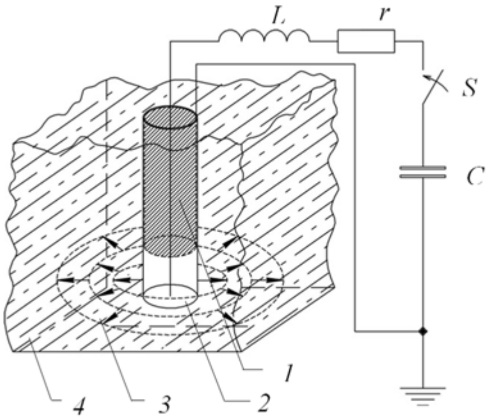

Figure 1. Scheme of plasma-blasting fracture of concrete: 1 – coaxial cable; 2 – electro-blast cartridge; 3 – shock-wave disturbances, generated by expanding plasma channel; 4 – concrete test specimen.

To increase the efficiency of electrical energy transformation 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 [8]. The cartridge was placed in a drilled hole in the concrete sample. During discharge, the wire explosion and the plasma channel formation occur. After the electrode gap bridging by a plasma channel, the great amount of electrical energy is transferred from the capacitor bank *C* into the plasma within a very short time. Joule heating of the plasma channel results in the extremely rapid channel pressure buildup and the 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 the shock and pressure wave disturbances forms a tensely-deformed material state and results to the formation of mechanical compressive, tensile, and shear stresses, causing the solid destruction. An enhancement of the mechanical fracture work (the pressure wave energy) produced by the plasma channel is the main goal of energy optimization.

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

Electrodynamic oscillating processes in the discharge circuit obeys the Kirchhoff's law:

$$L\frac{di(t)}{dt} + (R_{ch} + r)i(t) + \frac{1}{C}\int_0^t i dt = U_0 \, , \tag{1}$$

where L is the circuit inductance, μH; R_{ch} is the channel resistance, Ω; *i(t)* is the current in the circuit, A; U_0 is the charge voltage of a capacitor bank, V; *r* – an active resistance of the generator, Ω.

The electrical channel energy transformation into the plasma and shock wave energy is determined as:

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

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

The dynamics of shock and pressure waves in the polyethylene and concrete was analyzed due to the hydro-dynamical equations, in the form of equations of the conservation of momentum, mass, and energy in the Lagrangean coordinates for a cylindrical symmetry [9, 10].

The empirical equation for the discharge channel resistance before the wire explosion was determined as [6]:

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

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

$$R_{ch0} = \frac{l_{ch}}{s}\rho_{cop} \, . \tag{4}$$

Here, s is a wire cross section area, and ρ_{cop} is a specific resistance of copper. A specific energy of the copper wire is defined as follows:

$$w = \frac{1}{m}\int_0^t i^2 \cdot R_{ch} \cdot dt\,, \tag{5}$$

where m is the mass of wire.

The capillary plasma channel resistance $R_{ch}(t)$ after the wire explosion is determined through the integral of a current action in the form of Vaicel-Rompe [11]:

$$R_{ch}(t) = A_{ch} \cdot l_{ch}\left(\int_0^t i^2(t)dt\right)^{-\frac{1}{2}}, \tag{6}$$

where A_{ch} is a spark constant (in case of polyethylene A_{ch}=210 V·s$^{0.5}$·m^{-1} [3]).

Polythene compressibility has been described by the state equation. Since under electro-discharge technologies, the maximum level of pressure achieved in the solid is lower than 1000 MPa, it is possible to use the barotropic dependence in the form of $P=f(\rho)$ or a linear dependence of the shock wave speed D on the mass speed U in front of the wave:

$$D = a + bU\,. \tag{7}$$

By means of Rankine-Hugoniot equations [9], this equation was transformed into:

$$P = \rho_0 a^2\left(1-\frac{\rho_0}{\rho}\right)\Bigg/\left[1-b\left(1-\frac{\rho_0}{\rho}\right)\right]^2, \tag{8}$$

where P – the pressure in a material covered with a wave, ρ_0, ρ – the initial and current material density. For polyethylene, $\rho_0 = 0.94$ g/cm^3, $a = 2901$ m/s, $b = 1.481$ [9].

3. Blast-hole simulation results

The research and analysis of the energy conversion laws and the shock-wave dynamics were carried out for the electric circuit shown in figure 1. Several plasma blasting computer experiments were undertaken, using the concrete specimens of about 300×300×600 mm size. The diameter of the drilled hole is 26 mm, and its depth is about 300 mm. The hole was drilled at the distance of 300 mm from the concrete block surface. The length and diameter of a copper wire initiating the discharge were 100 mm and 0.2 mm, respectively. The generator circuit parameters varied within the ranges: U_0=(5–15) kV, L=1.22 µH, C=(224–1120) µF.

The simulation begins at the moment of switching on the generator commutator S (figure 1). The Joule heating of the plasma channel results to an increase of its conductivity. The internal energy, leads to the current amplitude growth (figure 2, a, b). The time period of current oscillations is about T=(0.3–0.5) ms for the chosen generator parameters. The positive feedback between the energy release and channel conductivity causes a build-up of internal energy of the plasma channel (figure 2, c). The electrical power deposition reaches (4–5)·10^8 W.

The explosive electrical energy of the channel results in a sharp increase of the plasma pressure up to (2–2.5) GPa, leading its expansion. The channel pressure is not stable; an 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 plasma channel. The channel expansion leads to the pressure pulse formation on the borehole walls (figure 2, d). An increase in the rate of energy deposition into the plasma channel tends to shift the pressure wave amplitude at the borehole walls to the higher values.

The generator capacitance and inductance leads to a damped oscillation in the circuit, thereby the discharge gap acts as a nonlinear resistance. During the oscillations, concerted changes of the discharge current, the voltage, and the channel resistance occur. The current and voltage oscillations lead to fluctuations of a power of the energy release in the plasma channel. Thus, during the first half period of the current oscillation, (50–80) % of the total stored energy is allocated in the channel. The ohmic losses in the circuit do not exceed (15-25) %. Further fluctuations of the energy have little effect on the plasma channel pressure and the radius. Thus, the main shock action on a destructible material is generated during the first current oscillation.

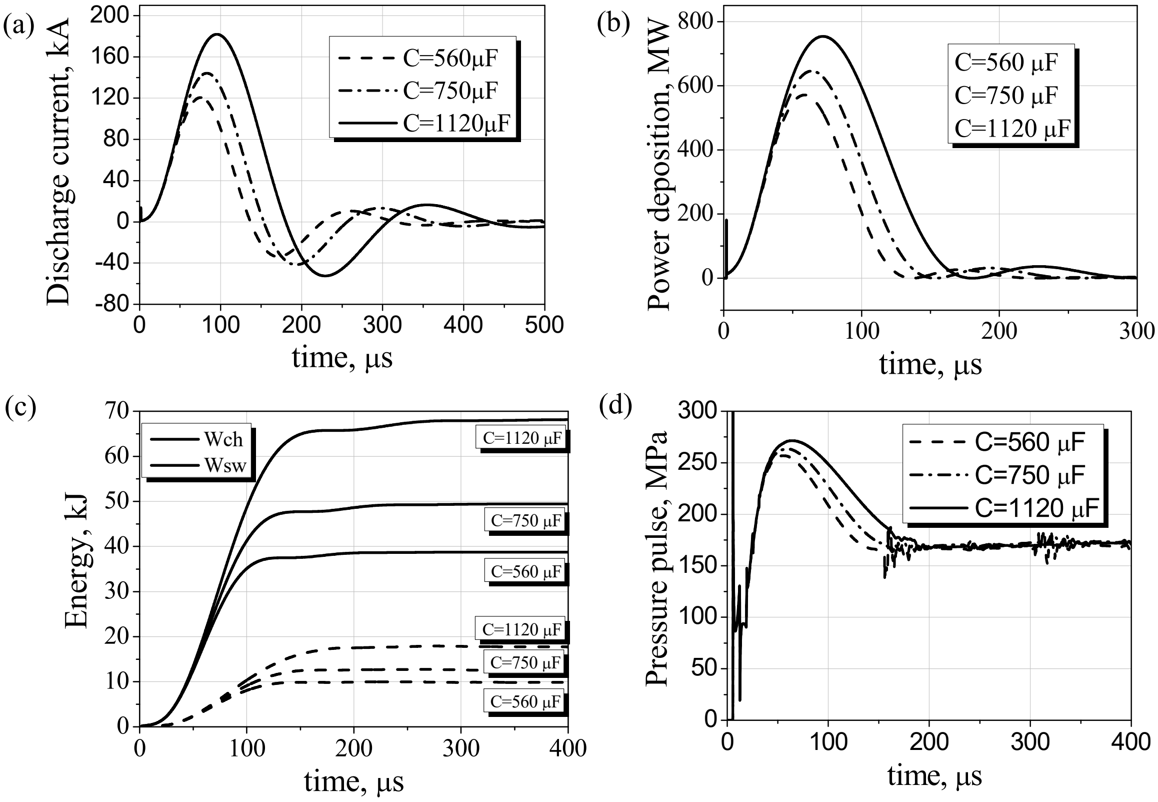

Figure 2. The time dependencies of the discharge channel current (a), electrical power deposition (b), channel (W_{ch}) and shock wave (W_{sw}) energy (c) and pressure pulse on the borehole walls for different rates of electrical energy deposition.

The amplitude and profile of the mechanical stresses causing the concrete destruction strongly depend on the pressure waveform produced at the borehole walls which, in its turn, is determined by the spatiotemporal distribution of the electrical power deposition in a plasma channel. The small channel radius leads to a sharp decrease in the stress-wave amplitude in the vicinity of the channel caused by the wave-energy divergence in the radial direction. The shock-wave disturbances in a concrete are damped along the way of their propagation, due to the wave energy dissipation. The figure 3 illustrates the radial and tangential stress distribution before the wave reflection from a free concrete specimen surface for various rates of the electrical energy deposition in a channel.

The obtained results showed that the rapid power deposition results in a higher amplitude of compressive stresses of the direct wave both in radial and tangential directions. However, a decrease of the rate of energy deposition into the discharge channel results to the formation of tensile tangential stresses causing the crack initiation at the smaller radial distance from the channel (figure 3, b).

The necessary condition for the main crack generation in a concrete is the formation of tensile mechanical stresses. The crack is initiated when one of the stress components exceeds the concrete tensile strength of about (5–10) MPa.

The wave dynamics shown in figure 3, demonstrates that the lower energy deposition rate leads to the higher amplitude of tensile stresses in tangential directions. In the case of the rapid deposition, the region of tensile tangential stresses of the direct wave is formed later. Figure 3 (a) shows, that mechanical stresses in radial direction are compressive along the distance from the channel till the free concrete surface.

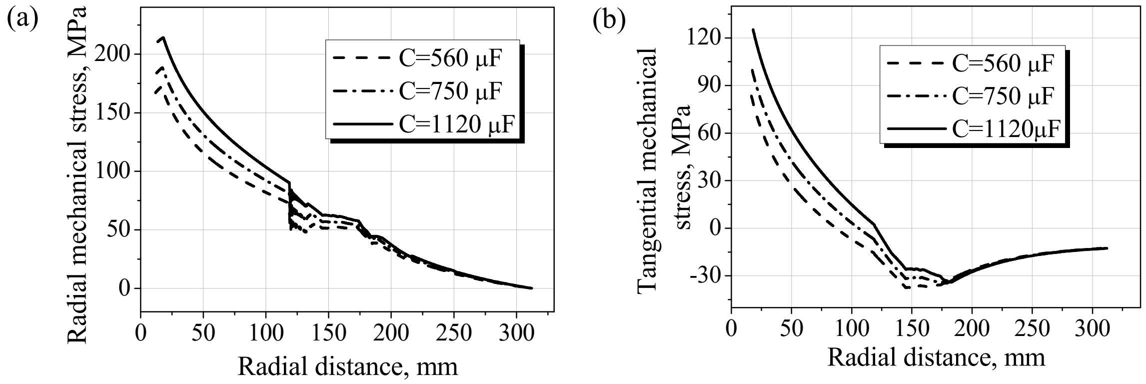

Figure 3. Radial distribution diagrams of radial (a) and tangential (b) mechanical stresses in the direct pressure wave in concrete (t=130 μs).

The fracture pattern of concrete specimen is defined by the resultant tensely-deformed solid state, formed by an interaction of the direct and reflected waves. A mechanical stress distribution, with an intricate profile generated by a superposition of the direct and reflected waves, is shown in figure 4.

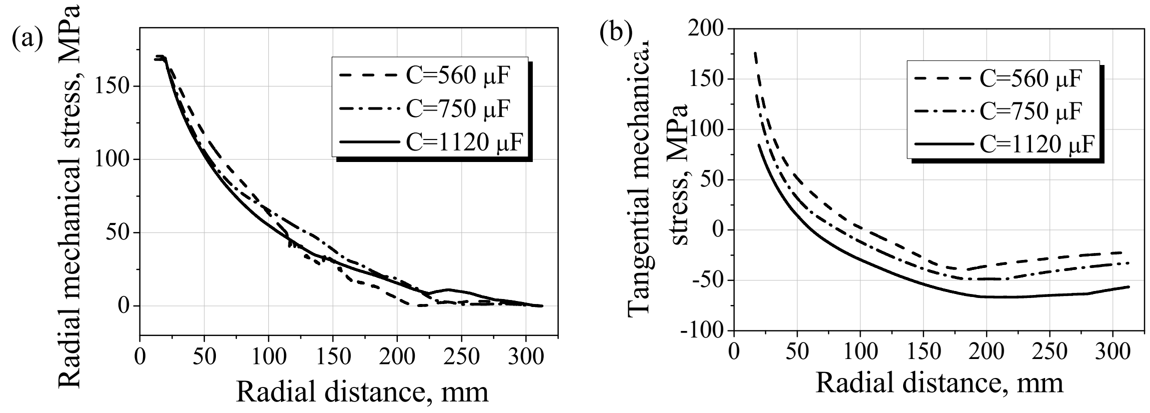

Figure 4. Radial distribution diagrams of radial (a) and tangential (b) mechanical stresses of the reflected pressure wave from the free concrete surface (t=280 μs).

The amplitude of compressive mechanical stresses of the wave is relatively law and lies in the ranges of material elastic deformation. It is shown that the region of tangential stresses is formed in the direct wave, but in the reflected wave, its amplitude is doubled. Formation of this area leads to the formation and development of radial cracks, oriented from the borehole wall to the free concrete surface. The increase of the rate of electrical energy deposition into the plasma channel tends to shift the amplitude of tangential stresses to higher values and extend the region of tensile tangential stresses from the borehole walls to the free material surface (figure 4, a). The mechanical stress level for the crack growth is rather low, in comparison with that of the crack initiation. That is why, the stresses shown in figure 4 are redundant for the crack propagation in a concrete.

Thereby, the results of electro-blast simulation have shown that the rapid power deposition produces an increase in the peak pressure at the borehole wall. However, because it is produced by a shock, the pressure pulse to the borehole walls falls rapidly, whereas slow power deposition produces a sufficiently sustained pressure pulse

4. Conclusion

At this stage of research and development of the blast-hole electro fracture of concrete, an essential gain of an efficiency of the solid disintegration has been achieved, and the possibility of material splitting-off at the free surface with a radial distance 0.3 m has been demonstrated. The results of simulation have shown a significant dependence of the stress-wave profile on the pressure pulse wave shape at the borehole wall which, in its turn, was determined by the rate of electrical energy deposition into the plasma channel. The analysis of stress-wave dynamics has shown that the rapid power deposition results in the higher amplitude of compressive stresses of the direct wave both in radial and tangential directions. The increase of the rate of electrical energy deposition into the plasma channel tends to shift the amplitude of tangential stresses of the reflected wave to higher values and extend the region of tensile tangential stresses from the borehole walls to the free material surface.

Acknowledgements

This work was supported by grants of RFBR № 14-08-01088 and RFBR № 16-48-700278.

References

[1] Burkin V Burkin V, Kuznetsova N and Lopatin V 2009 *J. Phys. D: Appl. Phys.* **43** 185204
[2] Vorobjev A and Vorobjev G 1971 *Pulse breakdown and destruction of dielectrics and rocks* (Tomsk: Publishing house TGU) p 223.
[3] Sjomkin B, Usov A and Kurets V 1995 *The principles of electric impulse destruction of materials* (St. Petersburg: Nauka) p 276
[4] Bluhm H, Frey W, Giese H, Hoppe P, Schultheis C and Sträbner R 2000 IEEE Trans. On Dielecrics and Elecr. v **7** pp 625–636
[5] Timoshkin V, Mackersie J and MacGregor S 2004 *IEEE Trans. Plasma Sci.* **5** 2055
[6] Naugolnyh K and Roy N 1971 Electric discharges in water (Moscow: Nauka) p 238
[7] Krivitskij E Dynamics of electro explosion in a liquid (Kiev: Naukova Dumka) p 208
[8] Kuznetsova N, Lopatin V, Burkin V, Golovanevskiy V, Zhgun D and Ivanov N 2011 *Pros. 17th IEEE Int. Pulsed power Conf.* (Chicago) pp 267–273
[9] Kinslow R 1970 *High-velocity impact phenomena* (New York: Academic Press) p 533\
[10] Rihtmyer R and Morton K 1967 *Difference methods for initial-value problems* (New York: Interscience)
[11] Wilkins M 1964 *Calculation of elastic-plastic flow, methods in computational physics* (New York: Academic) pp 211–264