Pulse Discharge in Dielectrics and Its Technological Applications

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Abstract - It is described physical base of electrical discharge technologies for dielectric material treatment, synthesis a new and decomposition of chemical combination, fragmentation, drilling and cutting solid material. It is formulated computer model which simulates channel propagation in liquid and solid media and allows to choice pulse generator parameters. Technology applications of spark in liquids and solids are illustrated.

1. Introduction

Electrical discharge technologies are based on energy transformation of the non-thermal and non-equilibrium discharge plasma in gaseous, liquid and solid dielectrics to energy of phase transitions, chemical reactions, mechanic work of material crushing. The main feature of such operation is the possibility to introduce high density energy to treated matter at the pulse made. The principal operation of the discharge consists of additive components: power electromagnetic radiation from UV up to radio range and fast change of electrical fields with speed up to 10^{11} V/ms, electron and ion action, shock waves which are transformed in pressure ones. Discharge plasma is unsteady and non-equilibrium plasma. It acts on material synergistically. So the interaction energy is more than sum of additive components.

In electrodischarge technologies spark and quasi - space discharges are usually used. The last glows only in gases and gas-liquid mixtures. To avoid current contraction and to keep sufficient working volume we reduce duration of discharge up to ~ 10^{-7} s, and enhance the velocity of electrical stress up to 10^{11} V/ms, and limit the current density, for example, by application of dielectric coating to electrode or barrier placement in a discharge gap. Such plasma is used for:

- activation of chemical reactions for synthesis of new compounds, for example, diamond-like films and ozone production;
- decomposition of molecule bonds or combinations in plasma-chemical reactions, for example, for water purification from metal-ions and organic inclusions, and production of light fractions of oil, and for nature gas-liquid conversion;
- drying of wood wares and timber.

The spark pulse discharges are used as tool [1-3] for:

- granulating and crushing of solid non-conducting materials and ware (big rocks, concrete slabs, railroad sleepers, solid wasters, grinding of crystalline quartz for overpure silicon production) [4-5];
- granulating and activation vegetable raw for increase of extraction;
- scaling of inner surfaces tube lines and heat exchangers;
- cutting and boring of hard materials (rocks, concrete) for example, drilling of deep wells;
- production of metal nanopowders and their oxides and nitrides which are synthesized discharge in vapors of electrical exploded metal wires.

Electrical strength E_b depends on distance, electrodes geometry, temperature, type and form of voltage, volt-time dependences, and parameters of propagating discharge channels and pressure waves caused by exploded expanding of channel in various media. These data which were generalized in [1-6] and lots of review articles allowed to simulate discharge development for determination of spark trajectory in treated inhomogeneous materials and needed parameters (voltage, current and duration) of pulse generators.

2. Simulation of discharge development

The formation of discharge channel results to transformation of the dielectric material into the conductive state due to operation of the strong electrical field. Instability of the processes driving the conductive phase formation and microinhomogeneity of the dielectric material result in stochastical meandering and branching of the propagating discharge channels. At the same time the trajectory of the channel depends on distribution of the electric field in treated material. The field distribution is determined by the electrode geometry, presence of macroinhomogeneities of conductance and/ or permittivities, and free space charges in a dielectric material. Therefore both stochastic and deterministic methods are required for adequate description of the discharge propagation.

Our model [6] allows simulating channel propagation as a stochastic process of fractal structure growth. The basic assumption of the model is the processes, which are responsible for discharge channel growth, and are determined by the local electric field and dielectric properties only. Therefore the probability P of the growth in any direction can be expressed as a function of the local field $\overline{E}^2$ and parameters describing the properties of the material. The growth probability P in any direction is assumed to be proportional to a square of the local field projection E_n on this direction, if E_n exceeds some threshold critical field E_c, and zero, if E_n is less than E_c:

$$P = \begin{cases} E_n^2 / Z, & E_n \geq E_c \\ 0 & E_n < E_c \end{cases} \quad (1)$$

where $Z = \sum E_n^2$ is the normalization factor (the summation is made over all possible growth directions). The critical field E_c is associated with threshold initiation of the discharge channel growth, i.e. no growth occurs if the local field is less than the critical one.

The electric field distribution within the dielectrics is calculated by the Gauss theorem in the differential form:

$$div(\varepsilon\varepsilon_0 \overline{E}) = \rho , \quad (2)$$

where ε and ε_0 are the relative and absolute dielectric permittivity, respectively, ρ is the free charge density. The boundary conditions are determined by the potentials and electrodes geometry.

Generation and transport of free charges in the channels and the treated material are described in terms of mobility by the Ohm's law:

$$\bar{j} = \sigma \cdot \overline{E} , \quad (3)$$

and continuity equation:

$$\frac{dp}{dt} = div\bar{j} , \quad (4)$$

where σ is the conductivity and ρ the charge density.

The conductivity of the dielectric material does not change in time, however the channel conductivity σ_{ch} changes during the breakdown to directly proportional to the released energy:

$$\frac{d\sigma_{ch}}{dt} = \xi \cdot \sigma_{ch} \cdot E^2 \quad (5)$$

Simulation is performed in real time. Any time step of channel growth on fixed length is calculated as

$$\Delta t = \frac{\theta}{Z} , \quad (6)$$

where θ is parameter of transition to the physical time.

On the base of stochastic (1, 6) and electrodynamics (2-5) equations a soft have been created for computer 2-D and 3-D simulation of discharge channel growth, and for determination of spatial-temporal and current characteristics of the channel development in inhomogeneous materials. We use simulation results for design of electrode systems of technological machines for choice of demanded parameters of the high voltage pulse generator. For example fig.1 shows the channel trajectory in liquid with ring carbon inclusion in rod-plane electrode system [7].

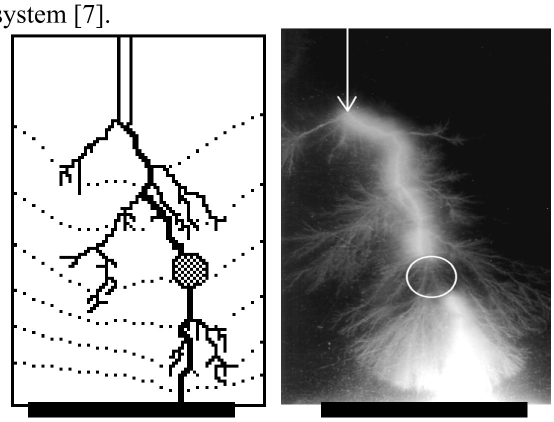

Fig.1. Discharge channel trajectory in dielectric with conducting inclusion: a) simulation, b) carbon inclusion within glycerin.

3. Technological application of spark discharge

The crushing operation of shock and pressure waves of expanding spark channel (fig.2) are used for various technological applications.

Principal schemes of processing based on spark pulse discharge is shown in fig.3.

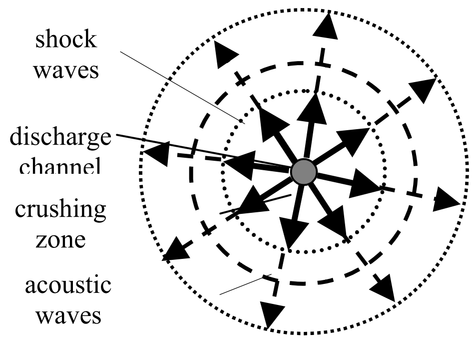

Fig. 2 Scheme of electrodischarge crushing

4. Surface cleaning

We use discharge technology for cleaning a scaled inner surface of pipe and molding presses. For example a few kilometers of steel and polyethylene tubes of the Tomsk plant of drinking water purification was cleaned from rust deposition by moving discharge electrode system.

Pipe line can be growing by rust up to full corking. The demolition of the scaled surface occurs in liquid-mineral deposition- tube borders.

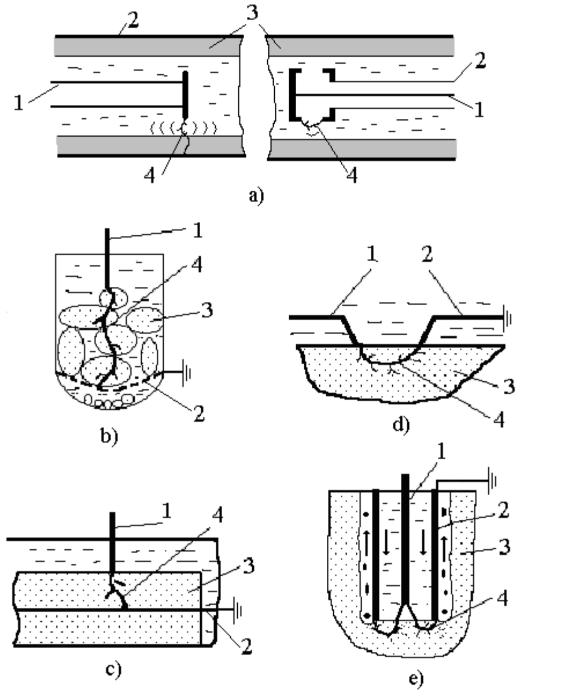

Fig.3. Schemes of the solid breakdown and crushing in liquid.
1. high-voltage electrode, 2. grounded electrode,
3. solid, 4. discharge channel.
a) scaling (cleaning), b) fragmentation,
c) concrete with reinforcement destruction,
d) discharge channel inculcation, e) boring.

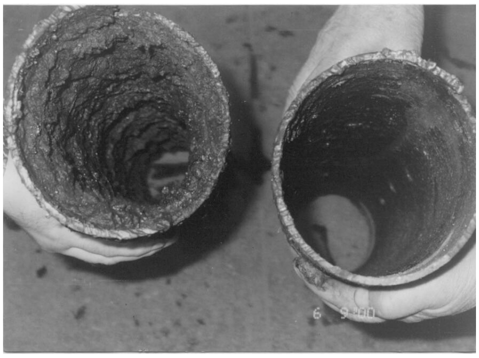

Fig.4. Tube before and after discharge scaling

Fig.5 Filter substance after (a) and before (b) discharge treatment

The similar pulse discharge method with smaller pulse generator is used to scale and to clean the multitude tubes of heat exchangers.

5. Fragmentation of the solid non-conductive materials

Our institute produces machines for discharge fragmentation of materials with productivity from 10 kg/hour (fig.6) up to 1 t/hour.

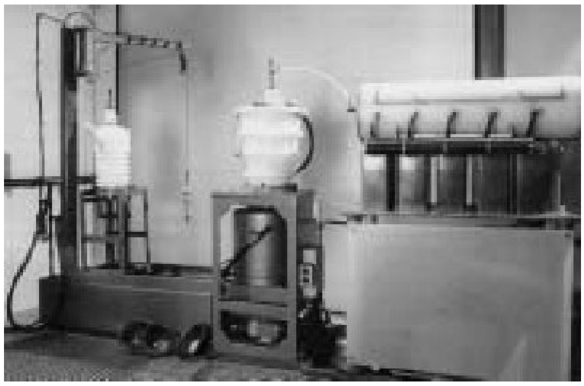

Fig.6. Machine for materials fragmentation.

These machines are used for fragmentation of multicomponent materials (for example preparation of hard waste for utilizing) and for extraction of selected component from solid or liquid.

6. Concrete destruction (railroad sleepers, sidewalk stones, concrete slabs, etc.).

Reinforced concrete utilization is reasonably realized in two stages: the first stage is to extract the reinforcing bars (primary disintegration) and the second stage is to put the finishing disintegration to unconventional or nonstandard fractions down to the dimensions suitable to be reused in new products.

At the first processing stage the electrical discharge technology based on the discharge development in concrete is the most effective. In this process the metallic reinforcing bar serves as one of the electrodes and in the process of concrete destruction does not significantly change their form.

Fig.7. Installation for concrete slab destruction.

7. Hard rocks and concrete cutting.

Discharge technology is appropriated for cutting of granite, gabbros, sandstone and concrete (fig.8,9). Early similar method was tested when cutted materials were placed in oil-insulating liquid. Using of nanosecond pulse duration (~$1.5 \cdot 10^{-7}$ s) and low impedance generator allowed to realize cutting in water.

The advantage of electro discharge cutting is low specific energy and low dependence from hardness of rocks (table 1)

Material	Specific energy of destruction, W, kWh/m^2	Calculated rate of cutting at frequency 25 pulse/sec, m/h
Sandstone	0.75	1.1
Granite	2.6	0.9
Gabbro	2.1	0.9
Concrete	1.7	0.9

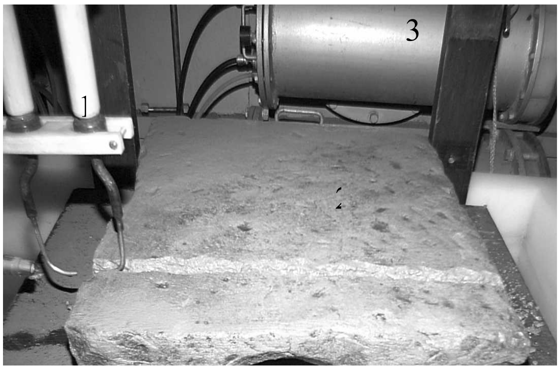

Fig. 8 Cutting of a sandstone. 1- electrode system; 2- sandstone; 3- pulse voltage generator.

Fig. 9 Spit in Gabbro

8. Drilling of wells.

In electrodischarge drilling the tool for destruction of rock is a bore tip (Fig.10). It consists of a system of high- voltage 1 and grounded electrodes 2, placed on bore face uniformly. Rate and efficiency of drilling depend on the interelectrode distance S. The expanding discharge cannels produce destruction and chipping the rock piece. The pit is filled with liquid. The dielectric strength of liquid is higher than one of the rock, the next discharge channel will be inculcated into the rock again in other interelectrode gap. Therefore the destruction of the face mining procedures is controlled automatically, that excluded the need of tip rotation and using other mechanical loads.

The rate of drilling holes diameter 300 mm in granite is achieved 10 m/hour.

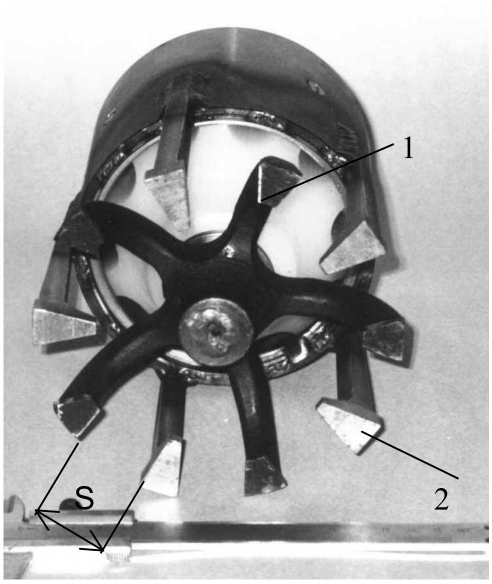

Fig.10 Bore tip for elecrodischarge drilling.
1. High- voltage electrode, 2. Grounded electrodes, S- Interelectrode distance.

Fig.11 Borehole in granite

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