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EXPLOSIVE DEVICE FOR CURRENT SWITCHING

URZĄDZENIE WYBUCHOWE DO WYŁĄCZANIA PRĄDU

The present paper deals with explosive devices for switching of kiloampere and megaampere current. The parameters of cumulation from a grooved surface and the parameters of shaped charge jet penetration into a barrier were analyzed depending on the initial properties of the explosive charge, the inert material and the barrier.
Keywords: explosive opening switch, cumulation

Przedmiotem pracy jest analiza zjawisk zachodzących w urządzeniach do wyłączania prądu o natężeniu rzędu kilo- lub mega- amperów, wykorzystujących energię wybuchu. Proces wybuchu analizowano w zależności od początkowych właściwości ładunku wybuchowego, materiału elementu napędzanego (masy inercyjnej) oraz materiału bariery.

1. Introduction

There is an actual task of energy transferring from an electric circuit to another one in pulsed power technology. To bring all or the specified part of energy stored in a circuit to a load, to form a leading or trailing edge of the pulse transferred to a load widely used explosive device for current switching.

2. Explosive devices for current switching overview

Explosive opening switches (EOS) operate on the principle of mechanical breaking of a metal conductor by detonation products or by dielectric material under shock wave loading.

Explosive devices for current switching which operate on the principle of high-speed breaking of a conductor can be divided into three main groups (based on the principle of action):

– EOS in which the conductor is broken by the detonation products (DP) of the high explosive (HE), located inside the conductor [1],
– EOS which throws a conductor on a ribbed barrier [2, 3],
– EOS in which the conductor is broken by dielectric cumulative jets [2, 4].

Speed of operation of an explosive opening switch is determined by the following factors: speed of conductor breaking and speed of electric arc quenching.

It seems that the most effective explosive opening switch is one in which the conductor is broken by dielectric cumulative jets (Fig. 1). There is no direct contact of the detonation products and the conductor, this explosive opening switch has a high speed of conductor breaking.

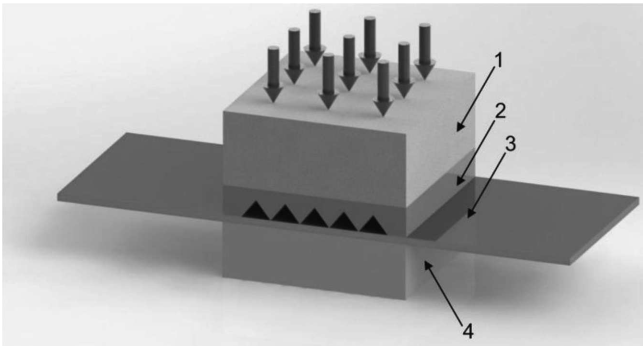

Fig. 1. Scheme of the explosive device for current switching 1 – high explosive; 2 – dielectric jetmaker; 3 – current-carrying conductor; 4 – dielectric barrier

3. Calculation of the cumulation parameters and the parameters of shaped charge jet penetration into a barrier

For the calculation it is considered that the plane shock wave begins to spread through jetmaker after the plane detonation wave falling on the jetmaker surface. The basic conservation laws (mass, momentum and energy) are performed across the shock wave front. The following system of equations can be obtained from the basic conservation laws:

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$$\begin{cases} u_{shock} - u_0 = \sqrt{(p_{shock} - p_0)(\upsilon_0 - \upsilon_{shock})} \\ D_{shock} - u_0 = \upsilon_0 \sqrt{\frac{(p_{shock} - p_0)}{(\upsilon_0 - \upsilon_{shock})}} \end{cases}, \quad (1)$$

where u_{shock} – the particle velocity in the shock wave,

u_0 – the initial particle velocity in the unshocked material,

D_{shock} – the shock velocity,

p_{shock} – the shock pressure,

p_0 – the initial pressure in the unshocked material,

υ_{shock} – the specific volume of the shocked material,

υ_0 – the specific volume of the unshocked material.

Theta equation was used as an additional relation connecting the thermodynamic quantities in the shock front.

Depending on the ratio of acoustic stiffness of the detonation products and the jetmaker material a reflected compression shock wave or a rarefaction wave will spread through the detonation products of HE. Relationship between the parameters of the falling detonation wave and the shock wave can be described by the following equation [5]:

$$u_{shock} = \begin{cases} \frac{D_{\exp}}{k+1}\left(1 + \frac{2k}{k-1}\left(1 - \left(\frac{p_{shock}}{p_H}\right)^{\frac{k-1}{2k}}\right)\right) (for\ compression\ shock\ wave) \\ \frac{D_{\exp}}{k+1}\left(1 + \sqrt{2k}\frac{\frac{p_{shock}}{p_H} - 1}{\sqrt{(k+1)\frac{p_{shock}}{p_H} + (k-1)}}\right) (for\ rarefaction\ wave) \end{cases}, \quad (2)$$

where p_H – the detonation products pressure at the Chapman-Jouguet,

k – the isentrope index of the detonation products,

$D_{\exp}$ – the detonation velocity of HE.

The calculations of the parameters of cumulation from a grooved surface are based on the analytical and numerical calculations of the RFNC – VNIIEF [6]:

$$V_{jet}^{NY} = V_{jet}^{N}\left[1 - \frac{\sigma_T}{\rho_0 U_{fs}^2} \cdot \frac{1 + \left[1 - 2(\sigma - 1)\sin^2\alpha\right]\cos\alpha}{\sin^2\alpha \cdot \cos\alpha(1 + 2.7\cos\alpha)}\right], \quad (3)$$

where σ_T – the dynamic yield strength of the jetmaker,

σ – the compressibility of the jetmaker,

α – half of the opening angle of the cumulative groove,

U_{fs} – the free surface velocity,

V_{jet}^{N} is determined by the following equation:

$$V_{jet}^{N} = U_{fs}\frac{1 + 2.7 \cdot \cos\alpha}{1 + 2(\sigma - 1) \cdot \cos^2\alpha \cdot f(a/\lambda)}, \quad (4)$$

where λ – the base of cumulative groove,

$f(a/\lambda)$ is a quadratic function determined by the following equation:

$$f(x) = 8.61x^2 - 13.92x + 6.31. \quad (5)$$

The parameters of shaped charge jet penetration into a barrier are calculated according to the hydrodynamic theory of armor-piercing.

A theoretical comparison of behavior of EOS has been performed. The jetmakers of polymeric materials with a high dielectric strength and a low, medium and high density (polyethylene (PE), polyoxymethylene (POM) and polytetrafluoroethylene (PTFE)) have been chosen.

Fig. 2 and Fig. 3 show some results of the calculation of the cumulation parameters and the parameters of shaped charge jet penetration into a barrier.

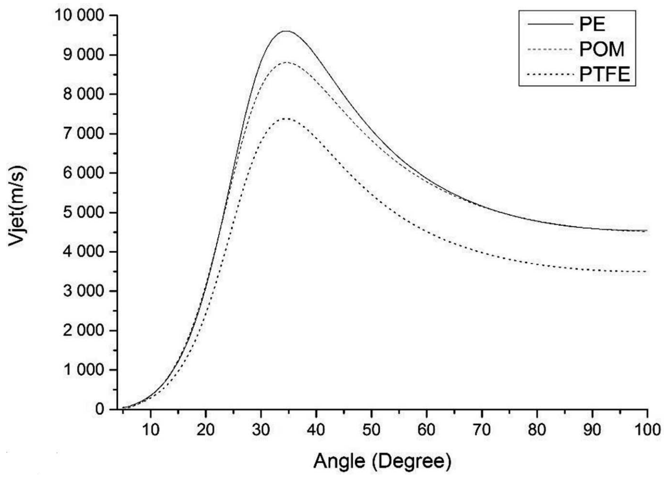

Fig. 2. Dependence of cumulative jet velocity on an opening angle of the cumulative groove

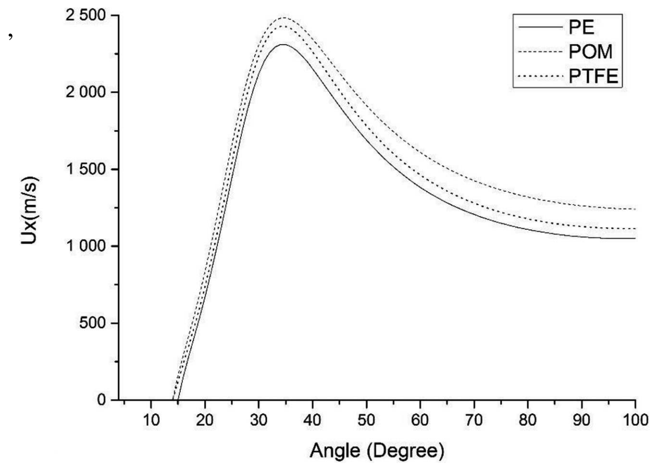

Fig. 3. Dependence of velocity of the jet penetration into a barrier on an opening angle of the cumulative groove

Maximum cumulative jet velocity and maximum velocity of the jet penetration into a barrier is observed in the range of the opening angle of the cumulative groove from 30 to 35 degrees. Maximum value of the jet penetration into the copper barrier is 2.3÷2.5 km/s for all jetmakers. The highest value of a penetration depth has PTFE jet, that is mainly due to the high density of PTFE.

For further studies POM as a material of jetmaker was selected, because:

– PE jetmaker has too low penetration depth into the barrier, due to its low density,
– PTFE cumulative jet has velocity less than ~20÷30% than POM cumulative jet in almost identical velocity of the jet penetration into a barrier.

There were preliminary experiments with different jetmakers and dielectric barriers. It was found that the proposed algorithm of calculation of the cumulation parameters and the parameters of shaped charge jet penetration into a barrier:

– has an error less 27% as compared with the experimental data for the calculating of cumulative jet velocity,

– has an error less 13% for the calculating of the depth of jet penetration into a barrier (TABLE 1).

TABLE 1
Experimental and calculated data for the cutting of a steel barrier by various jetmakers

Jetmaker material	Opening angle of the cumulative groove, degree	Penetration depth, mm	Calculated penetration depth, mm
POM	30	2,4	2,1
POM	60	2,3	2,2
PTFE	30	2,8	2,6
PTFE	60	2,9	2,8

4. Current breaking

Preliminary tests on breaking of circuit with kiloampere current pulse from capacitive energy storage system are carried out. The capacitive energy storage system parameters: capacitance 100 μF, initial capacitor voltage 4 kV, power circuit inductance ~10 μH.

In the dielectric arc-suppressor (dielectric barrier on Fig. 1) a mechanism was implemented to isolate each section of conductor breaking. The mechanism ensured the absence of electrical breakdown between adjacent current-breaking areas.

Jetmaker and high explosive with linear dimension 35 mm * 35 mm in the cross section was used. HE mass was 40 g.

The maximum current in the circuit: I_{max} =6.5 kA.

The time of current breaking (Fig. 4) from level I_{max} to level $0.1I_{max}$ was 2.4 μs.

EOS resistance increased with virtually zero to its peak value of ~30 ohms for 1.9 μs.

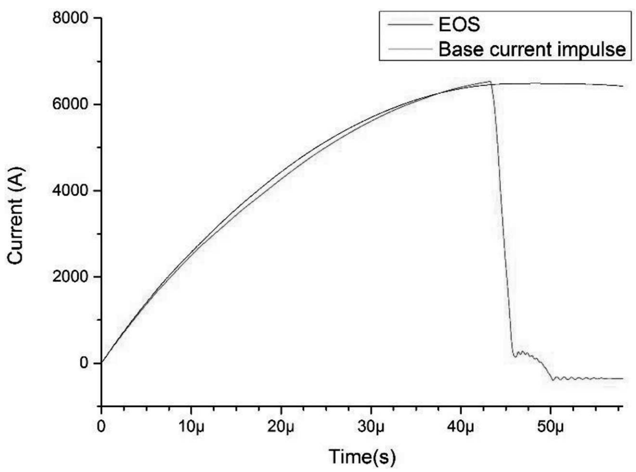

Fig. 4. EOS performance

Test on breaking of circuit with megaampere current pulse from a magneto-cumulative generator has been carried out. An axisymmetric EOS was used for the experiment. HE, jetmaker, conductor and arc-suppressor were coaxial cylinders. There were 11 cumulative grooves at the outer surface of the EOS, opening angle of the cumulative grooves was 30 degree, height of the cumulative grooves was 6 mm. Moment of the current switching was selected on a stage of weak current rise after reaching a maximum current derivative in order to change the current derivative as a result of current switching was pronounced.

In the experiment (Fig. 5) the value of current through the EOS reached 0.32 MA. The time of current drop from the maximal level to the zero level equaled to 2.7 μs (Fig. 6), EOS resistance increased from virtually zero to 0.1 Ohm. The maximum value of the current derivative was $-2.5 \cdot 10^{11}$ A/s during the conductor breaking.

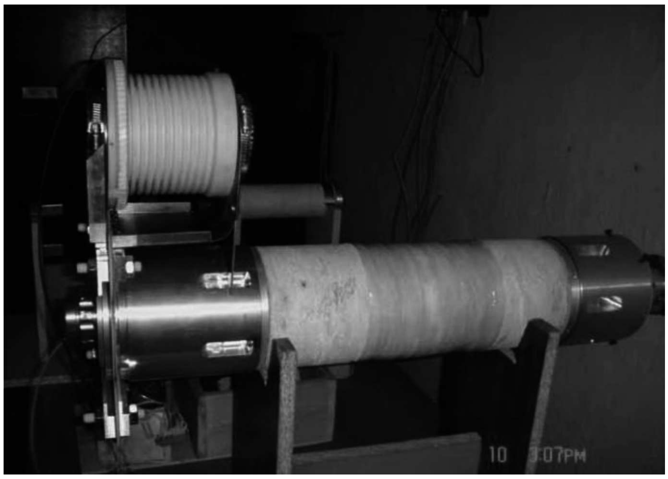

Fig. 5. Magneto-cumulative generator with axisymmetric explosive opening switch

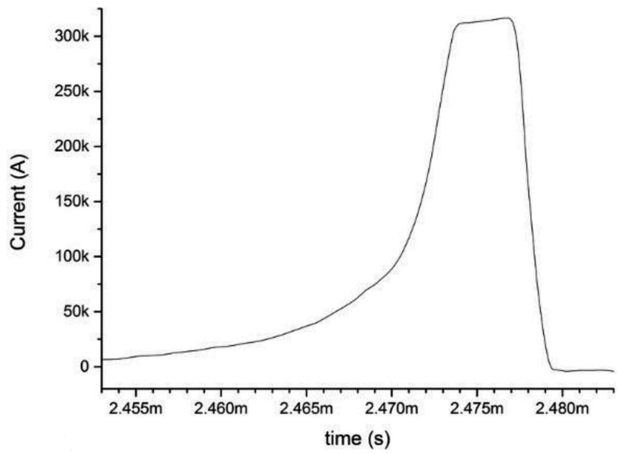

Fig. 6. Axisymmetric EOS performance

5. Conclusion

Calculation of the cumulation parameters and the parameters of shaped charge jet penetration into a barrier was performed. Spread of a plane shock wave through an inert material after a falling of plane detonation wave on the inert material was examined. It was considered that the shock wave in the inert material was sustained. A jet penetration into a barrier was calculated according to the hydrodynamic theory of armor-piercing.

The proposed calculation was validated experimentally: calculated parameters have an error less 27%.

Experiments on breaking of circuit with kiloampere current pulse from capacitive energy storage system and with megaampere current pulse from a magneto-cumulative generator are carried out. The time of current drop from the maximal value of 0.32 MA to the zero level was 2.7 μs.

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