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ELECTROMAGNETIC CONTROL OF THE SHAPED-CHARGE EFFECT

G. Shvetsov[1], A. Matrosov[1], S. Fedorov[2], A. Babkin[2], and S. Ladov[2]

[1] Lavrentyev Institute of Hydrodynamics, Lavrentyev Prospect 15, Novosibirsk 630090, Russia
[2] Bauman Moscow State Technical University, 2nd Bauman Street 5, Moscow 107005, Russia

This paper deals with electromagnetic actions used to control the shaped-charge effect at different stages of shaped-charge operation. A decrease in penetration of a shaped-charge jet is attained by passage of a powerful electric current pulse through it, production of an axial magnetic field in the shaped-charge liner immediately before shot, and production of a magnetic field in the conducting target material that is transverse to the direction of jet propagation. Results of experimental and theoretical studies of different versions of electromagnetic actions are analyzed, and the associated physical effects are considered.

INTRODUCTION

One of the methods of "intruding" into the physical mechanisms of the processes determining the efficiency of shaped-charge (SC) action in order to obtain desired changes in the course and characteristics of the processes is that of using different versions of electromagnetic actions. Depending on the problem solved, such actions can both increase and decrease the shaped-charge jet (SCJ) penetration. The present paper deals with electromagnetic actions used for the second purpose and implemented at different stages of shaped-charge operation (Fig. 1).

The results given below were obtained in theoretical and experimental studies of the effect of an axial electromagnetic field produced in the liner of a shaped charge (Fig. 1a) on the formation of a shaped-charge jet and the jet penetration into the target, the effect of the electric current passing through the SCJ and the effect of the self-magnetic field on the stability and disruption of the SCJ prior to its interaction with the target (Fig. 1b), and the effect of a transverse magnetic field produced in a conducting target on the final SCJ penetration into the target (Fig. 1c).

EFFECT OF ELECTRIC CURRENT ON THE STABILITY AND DISRUPTION OF A SHAPED-CHARGE JET

The action of a powerful electric-current pulse on a shaped-charge jet (so-called electrodynamic action) has been studied more comprehensively. A simple device for electrodynamic action consists of two metal plates connected with a source of electric energy (Fig. 1b). Usually, the device is located ahead of the target. The current starts to flow in the shaped-charge jet when the jet closes the electrodes. It is shown experimentally that action on a jet by a current of sufficient strength can considerably decrease the penetration capability of the jet or leads to its complete disruption [1–3].

The degree of decrease in target penetration by a shaped charge jet under electrodynamic actions of various intensities is given in Fig. 2. The figure shows experimental curves of the discharge current flowing through the shaped-charge jet from a 50-mm diameter charge for penetration into an aluminum target (in these experiments one of the electrodes was placed directly on the target). The figures above the curves denote the penetration depth in the targets corresponding to the present regime of electrodynamic action. In the absence of action, the penetration depth for the aluminum target is 365 mm.

The most probable physical causes of the decrease in the penetration of a shaped-charge jet into a target under electrodynamic action are the development of magnetohydrodynamic (MHD) instability of the necking type, which results in a decrease in the effective jet length and volume fracture of the jet material. MHD instability arises in the interelectorde gap when a current passes through the jet. Volume fracture of the shaped-charge jet is manifested by radial dispersion of the jet material after it leaves the interelectrode gap. This is followed by a decrease in the average density of the jet material and, as a consequence, a decrease in its penetration capability. Motion of the shaped-charge jet elements in the interelectrode gap produces prerequisites for volume fracture (intense heating and thermal softening or even melting of the material with simultaneous compressing action of electromagnetic forces), which are manifested when the jet elements leave the interelectrode gap (disappearance of the compressing action of electromagnetic forces with subsequent radial unloading, occurrence of a three-dimensional tensile stress state and, as a consequence, further dispersion of the softened material of the shaped-charge jet).

As follows from X-ray photographs, not only does electrodynamic action accelerate the development of natural plastic instability, leading to more rapid breakup of the shaped-charge jet into separate fragments, but it can also (having sufficient intensity) lead to “disk formation”. In this case, the jet material at the originally small narrowings begins to undergo intense axial compression with a sharp increase in the radius of the bulges. Thus, the jet segment becomes a flow of thin disks, which move after one another and have markedly greater diameter than the thickness and initial radius of the jet. Figure 3a,b gives two X-ray photographs of shaped-charge jets subjected to powerful current action, which are taken at different times denoted on the current curve (Fig. 3c). As can be seen from the X-ray photographs, the head elements of the shaped-charge jet, which have passed the interelectrode gap at the beginning of the current discharge, are practically not affected by the current by virtue of its smallness. In contrast, the elements of the middle and tail parts of the jet, which are under the maximum of the current discharge curve, undergo considerable deformations. Directly in the interelectrode gap, the “disk formation” process is manifested only slightly and, by virtue of the inertia of the material, it occurs only after the jet elements leave the action region.

Theoretical calculations of the development of MHD instability with passage of a current through a SCJ were performed for a model [4] in which the SCJ elements were treated as parts of an incompressible rigid-plastic rod of variable radius assuming that the rod cross sections retained their plane shapes during the entire deformation process. The force action of the current was allowed for by specifying the surface magnetic pressure. The model takes into account the thermal softening of the rod material, and the current density was assumed to be uniformly distributed over its cross sections.

The volume fracture mechanism is described using a model of a uniformly elongating, compressible, elastoplastic, cylindrical rod with a linear decrease in the strength yield of the material with rise in temperature [4]. Numerical results show that the velocity of radial dispersion of the jet material can be estimated from the simple energy relation assuming that after cessation of volume compression, the potential energy of the jet volume compression by the magnetic pressure is expended on doing work on fracture of the material, “quenching” of the kinetic energy of the axially convergent, radial motion of the jet particles, and on imparting them the kinetic energy of radial dispersion. In this case, the work of the jet material fracture was assumed to be equal to the potential energy of its bulk extension with the average stress determined by the current value of the strength yield.

The penetration of the SCJ segments subjected to volume fracture was calculated on the basis of the hydrodynamic theory of penetration combined with the concept of the critical velocity of penetration. It was assumed that after exit from the interelectrode gap, the average density of the jet material decreased continuously as a function of the velocity of its radial dispersion and the lower threshold of the jet velocity necessary for penetration into the target increases with decrease in density.

The behavior of shaped-charge jets under the action of a current pulse established by numerical simulation agrees, at least qualitatively, with X-ray photographs of jets subjected to electrodynamic action (Fig. 3).

The results of calculations of the decrease in the shaped-charge jet penetration into a target for this or that mechanism of jet fracture were compared with experimental data on penetration of aluminum target by the jets from a 50-mm shaped charge (see Fig. 2). Fair agreement between the calculated and experimental results for an aluminum target was obtained under the assumption that MHD instability develops when current flows through the jet not only in the interelectrode gap but also when the jet moves in the cavern inside the target.

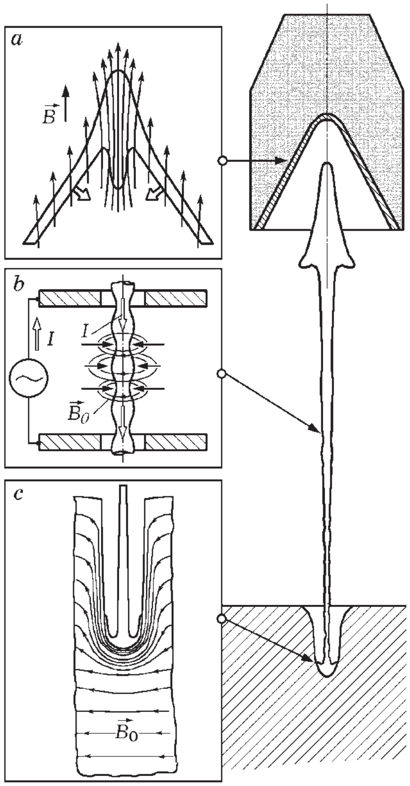

Fig. 1.

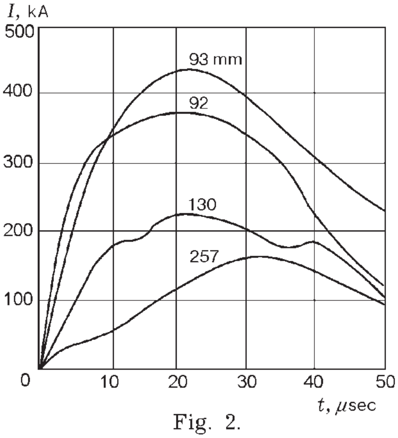

Fig. 2.

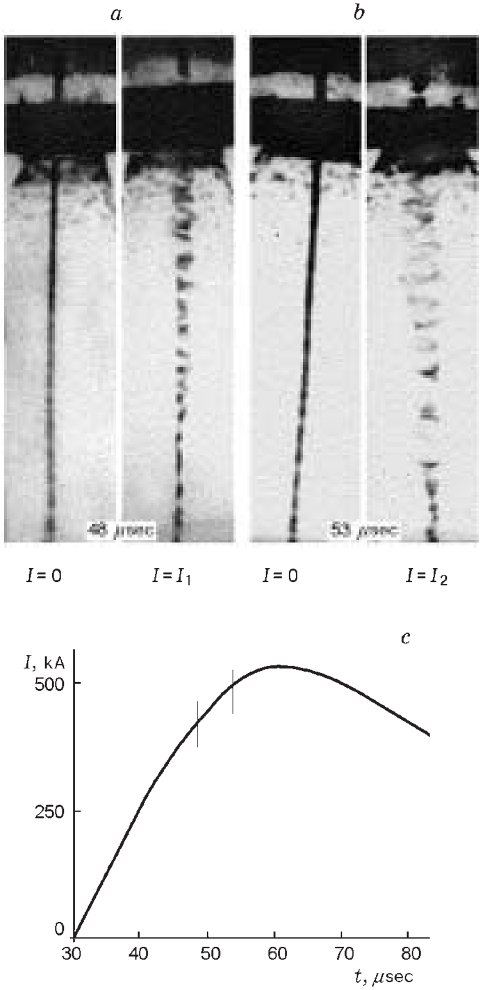

Fig. 3.

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EFFECT OF AN AXIAL MAGNETIC FIELD IN SHAPED-CHARGE LINERS ON THE FORMATION AND PENETRABILITY OF SHAPED-CHARGE JETS

In shots from shaped charges with an axial magnetic field produced beforehand in the metal liner of the shaped-charge cavity, the regime of liner compression that occurs is similar to the operation regime of a magnetocumulative generator (MCG) – a device for producing ultrastrong magnetic fields [5]. The principle of MCG operation is based on the phenomenon of magnetic cumulation – sharp amplification of an initial (relatively weak) field inside a conducting shell (liner) resulting from compression of the field due to collapse of the liner. The generation of strong magnetic fields leads to the occurrence of powerful mechanical, thermal, and electromagnetic effects. Producing conditions for the occurrence of such effects during shaped charge firing, one can affect the shaped-charge performance.

Simple estimates show that in the jet-formation region with "pumping" of a field in it to 100 T, the rate of heating of the material can reach 1000 K/μsec. The force action of this field is estimated by a magnetic pressure of about 10 GPa, which corresponds to the pressures resulting from HE detonation.

Combined with simultaneous powerful "thrusting" action of electromagnetic forces, powerful heating of the jet-formation region, capable of transforming the jet material not only into the liquid state but also into the vapor state with occurrence of thermal explosion, can lead to dispersion of the jet-forming region of the liner and the impossibility of shaped-charge jet formation.

The effect of a magnetic field on the jet-formation process was studied by numerical solution of the two-dimensional problem of oblique collision of plane jets of a compressible, perfectly conducting fluid with the presence in the jet material of a magnetic field oriented parallel to the collision plane [6]. Figure 4 shows jet flows that arise in the absence of a magnetic field (Fig. 4a) and in an initial field $B_0 = 5$ T (Fig. 4b). As can be seen from Fig. 4b, because of the presence of a magnetic field, the formation of a jet moving along the collision plane is impossible. The reason for this is the sharp increase of the magnetic field in the contact region, where the material of the colliding jets, which is forced to spread in the transverse direction, undergoes large tensile deformation along the magnetic lines, which ensures field generation.

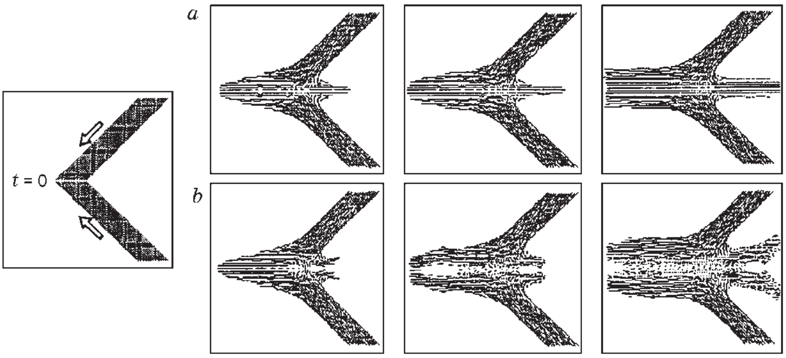

Fig. 4.

Experiments carried out with a 50-mm diameter shaped charge showed that the production of a magnetic field in the liner just before firing can sharply lower the penetration capability even for magnetic fields of tenths of a Tesla. When a field of about 1 T was produced in the liner, penetration was generally absent. In this case, on the surface of the steel target under the location of the charge, one observes only numerous shallow craters with dimensions not exceeding 5 mm and coppering traces.

Among the factors considered in [6] to explain the observed effect, the most likely is the assumption of sharp amplification of the magnetic field in the jet-formation region. The amplification of the compressed magnetic field at the apex, where the liner cross section is small, should be weak and should not hinder collapse of this part of the liner with formation of head elements of the jet. In the process of jet formation, the liner material, colliding along the charge axis, ceases to move in the radial direction and undergoes large tensile deformation in the axial direction, i.e., along the magnetic lines of the field produced in the liner. According to the effect of “freezing” of a magnetic field in a conducting material [7], this process should result in field generation and amplification directly in the material of the jet formed.

The question of what produces prerequisites for further dispersion of the jet if the magnetic field inside the jet exceeds the external field can be conclusively clarified after precision electrophysical and X-ray studies.

PENETRATION OF A SHAPED-CHARGE JET INTO A CONDUCTING TARGET WITH A MAGNETIC FIELD

The above-stated deformation conditions, leading to intense generation and amplification of a magnetic field in the jet, are also produced by high-velocity penetration into a conducting target with a transverse magnetic field produced in it beforehand [8]. In this case, according to the effect of “freezing” of a magnetic field in a material, field amplification is caused by the very large tensile strains along the magnetic lines that arise in the particles of the target layer adjacent to the penetrator.

The features of the flow and physical processes that arise when a shaped-charge jet penetrates into a perfectly conducting target with a magnetic field were analyzed for a plane scheme of interaction by a simplified quasi-two-dimensional model taking into account the force action of the compressed field [8]. The hydrodynamic theory of penetration was used as the basis, and the penetration process was treated as direct collision of two jets of incompressible fluids. In the jet corresponding the target, the induction of the transverse magnetic field B_0 at the initial time was considered uniform over the jet length. It was assumed that there was no magnetic field present in the SCJ material during the entire penetration process.

The magnetic field in the target increases only at the initial stage of shaped-charge jet penetration, and the further motion of the jet only leads to an increase in the dimensions of the region where the field reached its limiting value. In this case, as follows from calculations, the ultimate amplification of the magnetic field is determined by the equality of hydrodynamic and magnetic pressures at the interface between the jet and the target, and, hence, one might expect generation of strong magnetic fields during jet penetration.

As calculations show, when a shaped-charge jet penetrates into a target with a magnetic field, a region with a strong field should form not only ahead of the jet but also on the the lateral surface of the cavern. This is due to the fact that elongating in the transverse direction, the target particles on the path of the jet move aside and appear in the material layer on the lateral surface of the cavern, maintaining the high magnetic field resulting from deformation. In addition, generation of a magnetic field should occur directly on most of the lateral surface of the cavern because of its intense shear deformation during penetration.

The formation of a "magnetic" layer with a high magnetic field along the cavern boundary can result in one more effect – explosion-like dispersion of the material of the layer with collapse of the cavern formed by the jet. Prerequisites to such dispersion are due to intense Joule heating of the "magnetic" layer and the magnetic pressure acting in it.

According to the estimates of [8], for magnetic fields of ≈ 100 T, ensured by generation during high-velocity penetration, the velocity of particles of the surface layer of the cavern can reach several kilometers per second, which corresponds to the acceleration velocities of bodies driven by condensed HE. Powerful pulsed action on a penetrating shaped-charge jet can lead to its fracture.

Thus, during penetration of a shaped-charge jet into a conducting target with a magnetic field, effects can occur that lead to a decrease in jet penetration.

CONCLUSION

The studies performed showed that the use of magnetic fields in experiments with SC opens up new possibilities of controlling the shaped-charge effect. The effects studied previously can be of interest from both a practical viewpoint (decrease in the SC penetration in the target) and a methodical viewpoint in studies of the behavior of the material and physical characteristics of shaped-charge jets.

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