Generation of elastoplastic waves in shaped-charged (cumulative) jets and perforated barriers

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Abstract. The article focus on making use of electron-ion tools, based on the energy-spend processes of thermobaric dissociation, atomization and ionization of the facing materials in shaped-charge liners that kick in during explosive jet and slug generation, shaping of penetrators, fragments, and as they go through obstacles. These provide sufficient grounds for qualifying the jet structure in terms of its ionization not as fourth state matter, i.e. plasma, but rather as ‘third-and-a-half state’, meaning the matter is still solid but approaching the pre-melting condition. The different ability of the matter to transfer mass in the jet and slug (vortex and antivortex) based on its state has been stressed with the speed variation and phase transition being an indicator. In addition, the research provides estimates of the specific energy required for steel armor atomization that equals ~ 9kJ/g (~70kJ/cm³) to the extent sufficient to destroy to breach an obstacle.

1. Introduction
Ya. I. Frenkel's theory of metals already known for more than 90 years prevents researchers of the present day from disregarding the contribution made by an electronic subsystem of pressure-bearing materials into changes of their thermodynamic characteristics of P, V and T. This contribution stresses the importance of proper physical estimation of negative pressure for cases of scaled non-linearity of connections between pressure and volume affected by thermobaric field created by shaped charge explosives, when a delta of dP pressure lags or surpasses a delta of dV volume. As a consequence, "... an electronic structure reinforces, surfaces and clears up a road for a massive flow of atomic and ionic flow" of a shaped-charge jet's solid-state plasma [2]. Resulting from rotary drawing or flow turning process and annealing, various textures of antitank grenades shaped-charge liner can be achieved, leading to directional anisotropy of pressure-bearing metals in a deformation area, out of which a cone shaped-charged jet runs and spins (Figure 1) and which is therefore a result of a concurrence of a dominant torsional and tensile strain of metals forming a jet alongside negative pressure (when a pressure by volume derivative is dP/dV<0), and less intense compressional and shear strain in a slug alongside positive pressure (dP/dV>0) and variation of dP/dT.

Texture and therefore shaped-charge jet anisotropy of properties testify a solid state of materials in shaped-charged jets. Restoring losses of shaped charge piercing performance or spin compensation [2] is also a direct evidence of such solid state. A synergy of explosive barothermic effect applied, materials in different part of a shaped-charged jet modify their states (during its "lifespan" of just 1 ms length) from pre-melting to trans-melting and hyper-melting ones, the latter being a superheated solid state due to a concurrence of rapid (up to ~300 ns) shaped-charge jet thermobaric ionization and even more rapid (up to ~10 ns) inertial atomization of a slug. A process of copper dissociation, rapidity of which being measured in a picosecond range of 10⁻¹² s, completes within a thickness of a shock front. A pressure by volume derivative reversing its sign (at a point of dP/dV=0), pressure-loaded material passes through a metastable transient state creating oscillating loops visible on slugs' X-rayograms and moving shaped-charged jets, a hammer pattern (Figure 2) inside a barrier or compression elements, also visible on X-rayograms, if spraders of fixed conduction paths occur.
Figures 1 and 2 illustrate two processes, first being a very beginning of a neck formation processes in a shaped-charged jet, or so-called hammer effect of a shaped-charged jet that "beats" inside a barrier with plasma frequency with corresponding wave length of ~ 5 to 25 mm; and second being an aligning effect in a broken barrier (refer to page 80 in [2]).

Figure 1. Elastoplastic waves in a slug and shaped-charged jets (an aggregated result of analyzing a large number of X-rayograms of antitank grenades shaped-charge jets), where Lп is a length of a slug, Lр is an acceleration area of shaped-charge jets, Lкс is a length of a shaped-charge jet, L0 is a length of a shaped-charge jet before dividing into separate elements, P− is negative pressure and P+ is positive pressure, dP/dV - is a pressure by volume derivative, where dP is a delta of pressure, dV is a delta of volume, dρ - material discontinuity in a slug, shaped-charged jet and its elements, Lпэ is an area of elements' tranche division due to a domination of inertial forces on strength forces of solid shaped-charge jet elements.

Figure 2. Elastoplastic waves on a barrier's surface. Fluctuation of a deformation area generated by a hammer pattern of a sharped-charged jet penetrating into a barrier.

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2. **Harden jet evolution elongation - elastic slug compression deformation**

Even “thinking in the context of hydrodynamic approximation” while analyzing rayograms and protonograms of shaped-charged jets, an obvious inference is that a shaped-charged jet, speaking metaphorically, “is not still water, but a rapid flow” that creates vortexes and antivortexes in solid plasma with viscosity of $10^5$ Poise. Restrictions of incompressible flow models do not admit any uncontroversial explanation of achieving to throw out of bucket with viscous liquid (the Reynolds number) in microseconds, i.e. transferring at least a half of a shaped-charged liner mass into a shaped-charged jet of an antitank grenades within the same time interval. The work of S.K. Godunov and A.A. Deribas, published in the Combustion, Explosion, and Shock Waves scientific journal, which is a true handbook for ammunition engineers, in the 1970s, shows that the Reynolds number cannot exceed 4 during wave formation caused by explosive welding. This fact should have been taken into account when calculating the Navier-Stokes equation in the context of hydrodynamic approximation. For liquids the Reynolds number is $Re=20…300$, and vortexes easily appear. If water features viscosity of $10^{-2}$ Poise, then metal inside a shaped-charged jet features viscosity of $10^5$ Poise, which was determined by A.D. Sakharov and V.N. Meneev in their works in the 1960s. A metal instability pattern appearing in a slug while passing through a spinodal ($dP/dV=0$) bears evidence of vortex formation being close to a wave top (refer to Figure 1), when metal being affected by deformation either loses or gains resistance, following fluctuations of electron density in electron wind outbursts inside an accelerating or deceleration shaped-charged jet.

Being in different aggregative and high-stress states due to effects of axial, radial or circumferential stress, materials composing shaped-charged jet cone boundaries show unequal orientation and inertial, incl. hammer and aligning effects of plastic deformation in different parts of a shaped-charged jet and slug under the impact caused by a barrier or in flight deceleration. Just in nanoseconds both a shaped-charged jet and slug acquire corresponding gradients of axial, radial and circumferential velocities, Laplacian and other operators of a partial differential field, including differential coefficients of $P$, $V$ and $T$, incl. the first- and the second-order pressure by volume derivatives $dP/dV$, $d^2P/dV^2$ influencing a crystal lattice reaction on powerful undulation of a solid object's volume and a Grüneisen parameter $\Gamma_v = -\frac{2}{3} - 0.5V\frac{P}{\rho}$, where $\rho$ and $\bar{P}$ are the first- and the second-order pressure by volume derivatives correspondingly. Coefficients of kinematic momentum also change rapidly, as their value abruptly decreases from front to tail parts of a jet. Shaped-charged jet radial stress also decreases notably from the periphery to the core and depend on the material density and jet velocity.

3. **A synergy of barotermic effect or power engineering**

Effectiveness of a shape charge is defined by collapsing energy of shaped-charge liner, capacity of applied explosive agents, axial symmetry of charged elements and other factors and also depends on density and pace of detonation of explosive agents. Almost the whole list of trotyl-, hexogen- and octogene containing explosive agents widely used in manufacture industry meet a range from 1.4 to 1.9 $g/cm^3$ in density, from 6.9 to 9.1 km/s in detonation velocity and from 4.2 to 5.86 kJ/g in chemical energy output.

An energy source for atomization and ionization processes in loaded materials of liners is an shock wave actual profile formed by a relatively coarse and thick (for trotyl-containing 0.7±0.1mm, for cyclonite-containing 0.64±0.04mm, and for octogene-containing 0.37±0.07mm) detonating area spreading in different explosive agents with different detonating pace and with evolution of specific amount of chemical energy per every unit of an explosive agent, and energy consumption goes far beyond mentioned "consumers" [2].

If we look at a shaped-charged liner as at a transformer of explosive agent energy expended for plastic volumetric form change of liner material into the state of a jet and slug, then, counting specific characteristics in kJ/g while estimating a total energy balance between explosive energy and energy expenditure, it is necessary to take into account energy expenditure on atomization, for instance, of copper (4.72 kJ/g) and its light ionization (11.72 kJ/g) along with table values of explosive agents energy content. For example, for octogene it is 5.86 kJ/g, for hexogen - 5.8 kJ/g, for trotyl - 4.23 kJ/g,
for hexogen-TNT-based 50/50 explosives - 4.6 kJ/g, for octol 75/25 - 5.19 kJ/g, etc.). It is also necessary to estimate a mechanical momentum imposed to liner, which, according to the most optimistic estimations made by different sources, does not exceed 30% of a product of explosive agents mass by detonation velocity, i.e. \( i = 0.3 \frac{m}{v_D} \).

That being said, a shaped-charged jet is not a flow of interconnected ions (or atoms of copper without an s-orbital) in a form of perfect fluid. Instead, it is a multicomponent structure of ions, atoms and molecules with metallic bindings formed by overlapping external electron sheaths; those parts being bound form clusters with correspondingly different mass, material ionization, atomization and dissociation ratio, which allows us to consider such a structure to the fourth state of matter or, more precisely, to the “third– and– a– half” state of a solid plasma as mentioned before.

In relation to such a representation of a metal state inside a jet, it is highly possible to increase an accuracy of calculation concerning energy balance, considering that mentioned above processes of atomization and ionization are accompanied by dissociation of molecules of shaped-charged stress-loaded material.

The biatomic copper energy of dissociation commensurable with its enthalpy of melting, as well as dissociation of impurities are due to calculation in the right part of the energy balance equation. Then the equation looks like the following:

\[
A \sum_{i}^{k} m_{BB} Q_{BB} = \sum_{i}^{k} m_n E_a + \sum_{i}^{m} m_c E_u + \sum_{i}^{n} m_d E_d + \cdots,
\]

\( A \), the power selection ratio of a shaped-charge; 
\( m_{BB}, m_n, m_c, m_d \), correspondingly masses of an explosive agent, slug, jet and dissociated metals and impurities; 
\( Q_{BB} \), an energy content of explosive agents composing an explosive compound of a weapon; 
\( E_a, E_u, E_d \), correspondingly energy of atomization, ionization and dissociation of metals and impurities of shaped-charged materials.

On the grounds of the energy balance equation [2], an amount of energy required for atomization of armored steel was calculated and estimated as ~9 kJ/g (~70 kJ/cm\(^3\)), exceeding which breaking or penetration into a barrier is highly possible.

**Jet and slug – vortex and antivortex**

Incredible as it may seem, but physics and mechanics of discrete environment (as it can’t be unbroken, if all the used materials are of industrial purity degree), as well as atomic-ionic deformation kinetics with its dislocational mechanisms of scaled plastic deformations of materials, allowed to increase mass characteristics of penetrating quality >1 mm of armor up to 1 g of explosive charge of antitank grenade. Herewith, industrial purity of M1 monomorphous copper has never exceeded 99.9% Cu. The necessity of compliance with scientific honesty, as well as of metal physical culture improvement for shaped-charged jets consisting of only three parts development, were subtly and accurately highlighted by academician V.M. Titov. Further research and improvements in this field could allow the scientific community exploring shaped-charged jets to go beyond speculations, anticipations and obvious fiction cultivated by some scientists in terminology of academician Kruglyakov E.P. [5]. Such speculations of the last two decades include the following: "a new theory of cumulation with relief shaped-charged liner", energy emergence from nowhere, as well as "metal explosion with bond energy exposure".

Considering scientific honesty, mentioned above [3], there is no need to further increase the number of coefficients in the Lavrentiev equation and collect so-called numerical and engineer methods of a shaped-charged jet penetration capacity estimation that during the last several decades remain bivariate and do not include rapid vortex and antivortex bi- and trifurcated processes appearing in three-dimensional deformation areas in slugs, out of which solid shaped-charged jets
“come unscrewed” rapidly, in microseconds. Solutions of equations calculated with the help of modern computers remain approximate and apply only to two-dimensional spaces, where a vortex-antivortex twain of a shape-charge jet+slug type may appear [2], and they would have been needed to make into digital form the equation in full. Such an approximate nature of two-dimensional models and absence of equations applicable for three-dimensional spaces lead to the fact that further development of Frenkel's and Brigman's theories, as well as increase in productivity of modern computers could rapidly change the distance between the Schrödinger equation, Navier-Stokes equation and "forging workshop" like three-dimensional center of deformations in a slug, out of which a shaped-charged jet "comes unscrewed" in a "three-and-a-half" overheated, but still solid state of plasma bearing gradients of velocity, leaving energy vortexes and antivortex jet+slug, Laplacian and other operators and finally "hammer and aligning or conductor's effects" [2].

Reference

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