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Kinematics of the shaped charge jet formation process

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Abstract. Based on the review of scientific and technical literature, an analysis is made of the problems of the modern theory of formation, extension and destruction of the shaped jet. The focus of the research is on the kinematics of the formation of a shaped jet based on the approach of operating with the characteristics of a real metal when the velocity vector of the cumulative jet is the result of three vectors: strain, strain and displacement of the shaped jet's material. The numerical experiment of the functioning of the shaped charge is carried out, and the procedure for evaluating the calculation results is proposed. The obtained data correlate with existing knowledge about the physics of the cumulation process.

1. Introduction

To date, shaped charges are widely used in military and civil industries. The use of the cumulative effect opens up opportunities for increasing the effectiveness of the means of destruction of weapons and ammunition, borehole perforation during oil and gas production, cutting dimensional structures under difficult or dangerous conditions for humans, performing separation operations in conditions of limited energy sources, etc.

The mechanism of formation of a shaped jet, based on the ideal incompressible fluid model and experimental data, was independently developed by M. Lavrentiev and G. Birkhoff [1]. The hydrodynamic theory of cumulation explains the process of formation of a shaped jet during oblique collision of plates thrown either by detonation products or the explosive compression of axisymmetric metal facings, and is based on classical kinematic schemes of the theory of jet formation, operating with vectors of velocity of the cladding walls under conditions of pressure of detonation products and the speed of the two planes connection point.

The classical mechanism of jet formation is described in paper [2]. A detonation wave initiated in a blasting explosive of a cumulative charge propagates in the direction of the charge axis. The pressure of this wave and the expanding detonation products is so great that the strength of the lining is negligible compared to the transmitted load. That is why, the lining material can be considered as an inviscid liquid. In fact, the effect of the generated pressure on the short cladding produces the speed of V_0, which action vector is on the bisector of the angle formed between the perpendiculars to the initial and deformed surfaces of the cladding. According to the kinematics of shaped jet formation relative to the connection point of two surfaces, the speed of a point on the outer plane of the cladding will be equal to the difference of two vectors: the speed of the walls and the connection speed of the planes, and the jet and jet tail will move in opposite directions along the charge axis.

However, the experimental results, namely the data reflecting the specificities of the behavior of the metal under conditions of the formation and extension of the shaped jet, as well as at penetrating the barrier, have led to the refinement on the hydrodynamic theory. The main characteristic of a

shaped charge – piercing action – is to a greater extent determined by the maximum length of a shaped jet, therefore, the researchers and engineers are actively studying the processes of shaped jets stretching and fractures [3-5]. In attempts to predict the destruction of the jet, as well as ultimate tension, the scientists [6] identify the problems that require further research:

1. The existing models of stretching and fracture of jets, and the conclusions drawn by various authors are not consistent, although a collating of theoretical dependences with experimental data is generally satisfactory.

2. In the experiments, the dependence of the limiting elongation of the jet on the structural-mechanical characteristics of the metal (grain size, hardening, texture [7-11]) is manifested, despite the fact that the hydrodynamic model does not predict the behavior of the metal under conditions of a cumulative jet.

3. The reasons for the possible anomalous elongation of the material of the shaped jet before destruction, as well as the dependence of this ultimate elongation on the initial diameter and density of the jet, are unknown.

4. The reasons for the appearance of initial perturbations causing the destruction of the jet into many fragments are unknown.

5. The dependence of the ultimate elongation and the nature of the destruction of the jet on the chemical (phase) composition and degree of purity of the metal.

That is, despite the fact that in the classical hydrodynamic theory the lining material is considered to be an inviscid liquid, during jet formation and tension it exhibits properties characterising crystallites.

2. Materials and methods

As it was mentioned above, the studies of the behavior of shaped linings metal are usually carried out experimentally, and only their results are processed by computer-software systems, since a rigorous and complete description of the behavior of real metals during deformation causes certain difficulties [11]. However, one agrees with the fact that the features of modern numerical simulation environments significantly expand the boundaries of the possibilities for studying the formation of a shaped jet, for example, at the initial stages of research. Using numerical modeling tools, it is proposed to explain the kinematics of the formation of a cumulative jet, using the characteristics of a real metal. According to the results of the analysis of the researched problem the following approach seems to be quite promising - the velocity vector of the shaped jet is the result of three vectors: strain rates, deformation and movement of the material of the cumulative jet.

The strain rate is the change in the degree of deformation per unit time or the relative displacement of the volume per unit time as in equation (1):

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} [s^{-1}].$$

(1)

Using the capabilities of numerical simulations, one can track the strain rate as the ratio of the relative elongation of the computational cell (Lagrange approach) to the length of time in which the selected metal volume was deformed.

Here the speed of deformation is the speed of movement of the deforming tool. During jet formation, the deforming tool is a detonating explosive; therefore, we assume that the deformation rate is equal to the detonation velocity of a blasting explosive, from which the main charge of the shaped charge is formed.

The speed of movement of the material is the speed of displacement of certain points of the body during deformation. The capabilities of modern modeling environments make it easy to track the position of material points and process the results.

Using the Ansys Autodyn numerical simulation environment, it is possible to select sections of the computational space with the possibility of further processing of the calculation results. The operation of an axisymmetric shaped charge of caliber 50 mm in 2-D space is considered and the Lagrange-

Euler solver is used, and the nodes of the metal of the cumulative cladding are described using the Lagrangian method. The material of the cumulative lining is copper, the explosive is octol, the case material is steel grade 1006, and the surrounding space is air. Figure 1 shows the shaped charge, which functioning is studied in this research:

Figure 1. Shaped charge.

The JWL (John-Wilkins-Lee) equation of state is used to describe the behavior of explosives as in equation (2):

$$P_E = A_1\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B_1\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E_0}{V}$$

(2)

where P_E is the pressure; $V = 1/\rho_B$ – specific volume; ρ_B – the density of the explosive; E_0 – specific internal energy per unit mass; A_1, B_1, R_1, R_2 and ω are constants.

The equations of state of shaped lining are based on the shock model. In this case hardening is ignored, because, according to the physics of the process, the lining behaves like a liquid under high pressures and temperatures during deformation.

There is an empirical linear relationship between the detonation velocity and mass particle velocity u_p, which holds for most solids and liquids over a wide range. In Autodyn code, this relationship is defined as in equation (3):

$$U_S = C_0 + Su_p$$

(3)

where is S a constant reflecting the slope of the dependence $U_S(u_p)$, and is C_0 the speed of sound in the substance.

Then it is convenient to present in the form of Mi-Gruneisen an equation based on the Hugoniot shock dependence as in equation (4):

$$P = P_H + \Gamma\rho(E - E_H),$$

(4)

where $\Gamma\rho = \Gamma_0\rho_0 = const$, $\Gamma = B_0/(1-\mu)$ – Gruneisen coefficient, B_0 – constant, $\mu = \rho/\rho_0$ – compressibility; ρ_0 – reference density; P_H – Hugoniot pressure as in equation (5):

$$P_H = \frac{\rho_0 C_0^2 \mu(1+\mu)}{\left[1 - (S-1)\mu\right]^2}$$

(5)

and E_H – Hugoniot energy as in equation (6):

$$E_H = \frac{1}{2}\frac{P_H}{\rho_0}\left(\frac{\mu}{\mu+1}\right).$$

(6)

The equations of state of the steel shell are also subject to the shock model of Shock. The steel sheath strengthening model is described by the Johnson-Cook equation, which determines the yield strength Y as in equation (7):

$$Y = (A + B\varepsilon_p^n)(1 + C\log\varepsilon_p^*)(1 - T_H^m),$$

(7)

where ε_p is the effective rate of plastic deformation, $\varepsilon_p^* = \dot\varepsilon_p/\dot\varepsilon_0$; $\dot\varepsilon_0 = 1\,\mathrm{s}^{-1}$ is the normalized effective rate of plastic deformation, $T_H^m = (T - T_{room})/(T_{melt} - T_{room})$ is the homologous temperature, T_{melt} – is the melting temperature, T_{room} – room temperature, A, B, C, n and m are constants.

3. Calculation results and evaluation

The distortion of a dynamically changing grid calculates the deformation of the selected element and calculates the deformation rate of the material, by changing the coordinates of the selected elements - the velocity of movement. The distortions of the computational grid during numerical simulation are presented in figure 2:
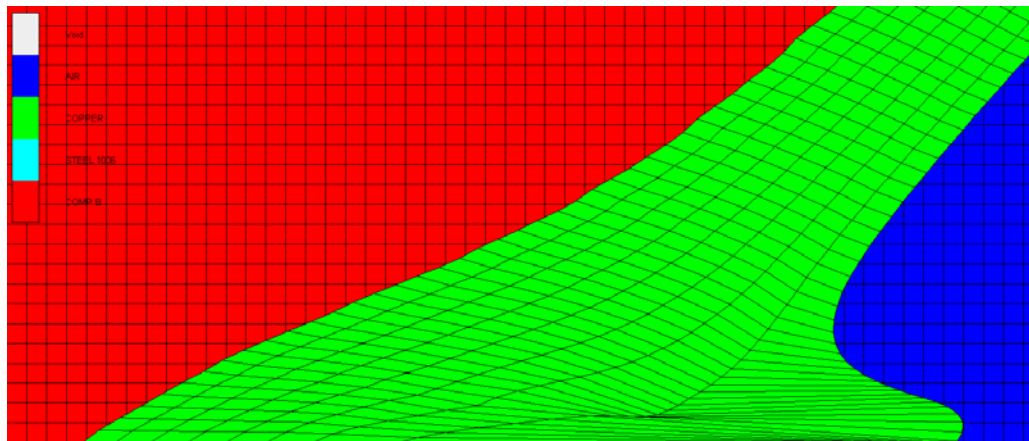
Figure 2. The result of calculating the functioning of the shaped charge, t=4 μs.

According to the statement of the problem and the results of the test calculation, the strain rate is equal to the detonation velocity of the explosive $v_1 = 7.98$ km/s, velocity of the deformation $v_2 = 2.9 \times 10^5\,\mathrm{s}^{-1}$, velocity of the material's movement $v_3 = 1.35$ km/s.

4. Conclusion

Despite the fact that in the classical hydrodynamic theory of cumulation, the material of the shaped lining is considered to be an inviscid liquid, during jet formation and tension it exhibits properties characterizing crystallites. According to the finding of the research, the following direction of further research seems to be promising, where the kinematics of the formation of a cumulative jet is based on an approach based on operating the characteristics of a real metal - the velocity vector of the shaped jet that is the result of three vectors: strain rates, deformation and movement of the material of the cumulative jet.

As a result of numerical modeling of the shaped charge functioning and estimation of the calculation results, we obtained the following characteristics: strain rate is equal to the detonation velocity of the explosive v_1= 7.98 km/s, velocity of the deformation v_2 = 2.9 $10^5 \, s^{-1}$, velocity of the material's movement v_3 = 1.35 km/s.

Therefore, by controlling the given characteristics, it is possible to control the speed and, consequently, the mass-energy characteristics of the shaped jet, which opens up a promising direction for research aimed at increasing the efficiency of the functioning of shaped charges.

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