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DESIGN TECHNIQUE FOR CALCULATING FUNCTIONAL PARAMETERS OF A ROTATING SHAPED CHARGE WITH PRELIMINARY HEATED LINER

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Abstract

The paper considers a separate issue of the shaped charge functioning, i.e., functioning of a rotating charge under preliminary thermal action on its liner. Estimates of two oppositely directed factors are provided: 1) increase in the shaped-charge jet dynamic plasticity (limit elongation coefficient); 2) increase in the jet susceptibility to centrifugal destruction. These factors are activated by preliminary thermal action on the shaped charge liner in the jet heated in excess of usual parameters. The so-called "thermal" increase in the limit elongation coefficient was estimated using empirical and theoretical dependences of this value on the shaped-charge jet parameters, and on the characteristics of its material. Strength dependence on temperature was accepted as linearly decreasing. Centrifugal factor was estimated based on the law of kinetic moment conservation taking into consideration the gradient nature of stretching and, up to a certain point, the radial thinning of jet elements. The moment of centrifugal and strength forces relationship reaching the critical value was accepted as the beginning of the jet element centrifugal destruction. From this time moment the jet radial extension started. The law of decompaction of its enlarging part was taken from studies previously conducted by the authors. It was demonstrated that the two considered factors acting in the opposite directions in a jet were in compliance with each other ensuring optimal preliminary heating of the liner and penetration effect with a local maximum

Keywords

Shaped charge, jet, heating, elongation, rotation, centrifugal destruction

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Introduction. Shaped charges (SC) improvement and issues concerning optimization thereof in order to achieve certain goals continue to arouse the interest of researchers specializing in the explosion cumulative effect.

Development proceeds both in traditional areas (for example, search for new materials in cumulative liner [1–3] and taking into account the influence of imperfections in the cumulative assembly shape [4, 5]), as well as in non-traditional approaches (thermal or electromagnetic effects on the shaped-charge liner (SCL) or on the shaped-charge jet (SCJ) created by a charge [6–10]). Most of these studies consider shaped charges under stationary conditions, and less commonly rotating shaped charges is examined. The listed factors with respect to SC could be considered as different control factors. But could they be interconnected with each other? For example, could it be possible to expect a positive effect under simultaneous thermal effect on SCL and rotation of the SC; as of today, this issue still remains unclear.

The idea of a shaped charge with preliminary thermal effect on its liner is known since the 1990s [6, 7]. Effect on the liner was carried out using a gas generator with time advance in regard to the detonation, and in such a way not to cause thermal initiation of the explosive [8]. SCL preliminary heating affects the SCJ temperature ΔT increase. This leads to an increase in dynamic plasticity, which indicator is the coefficient of the jet limit elongation n_{lim} [1]. An increase in the length $nl_0 \le n_{\text{lim}} l_0$ of jet penetrating into the target leads to increasing the penetration depth L into the target, which was registered in Ref. [6, 7]. The jet penetration depth L into the target is influenced not only by the jet length, but also by other parameters, in particular, by the jet density ρ_{j} and by the target density ρ_{t} that are interconnected between each other according to the Lavrentiev's formula

$$L = nl_0 \sqrt{\frac{\rho_{\text{j}}}{\rho_{\text{t}}}}. \tag{1}$$

However, the known experimental data [6, 7] on the increase in penetrating effect of a thermal SC were obtained under stationary conditions, i.e., an SC under experiment was immobile. At the same time, real SC as part of more complex devices is in motion and often rotates in flight. Moreover, for a number of common explosive devices, the characteristic rotation frequency is relatively low, i.e., up to 30 s^{-1} [11]. But, as the SCL collapses during the SCJ generation and its stretching, the moment of inertia is continuously decreasing and the rotation frequency is increasing. With significant unwinding, volumetric centrifugal destruction of a jet is possible leading to a decrease in its average density ρ_{j} and, according to Lavrentiev, to a decrease in the penetrating ability L. Centrifugal jet destruction would be manifested the stronger, the lower material strength is, i.e., the dynamic yield strength Y.

Thus, two opposite factors would appear in the operation of a rotating thermal SC under an increase in the liner initial heating ΔT. These are SCJ additional thermal elongation and its material thermal and centrifugal decompaction. As of today, it still remained unclear, which of these factors would prevail. It was necessary to give an answer to this question; and this was the *work purpose.*

Techniques for calculating parameters of the rotating shaped charge action. Our study was carried out by calculation and theoretical approach for calculating the effect of a SC with thin-walled liner, i.e., the V.M. Marinin approach [12]. In addition to traditional calculation of the major cumulation parameters [1, 12], thermal and rotational effects were calculated [13, 14]. Thus, the SCJ thermal elongation was determined based on the ratios for coefficients of current (n) and limit ($n_{\lim}$) elongation:

$$n = \begin{cases} 1+\dot{\varepsilon}_{z0}t & \text{at} \quad 1+\dot{\varepsilon}_{z0}t < n_{\lim}; \\ n_{\lim} = A + BR_0\dot{\varepsilon}_{z0} & \text{at} \quad 1+\dot{\varepsilon}_{z0}t \geq n_{\lim}, \end{cases} \tag{2}$$

$$n_{\lim} = 5.36\left(\frac{\rho_j \dot{\varepsilon}_{z0}^2 R_0^2}{Y}\right)^{0.39}, \tag{3}$$

where t is the current time; $\dot{\varepsilon}_{z0}$ is the initial axial velocity gradient; R_0 is the SCJ element initial radius; Y is the material strength characteristic under the jet conditions (dynamic yield strength of the material); A and B are empirical constants.

Formulas (2) are the formulas for current and limit elongation coefficients that are not containing thermal characteristics. Theoretical formula (3) for the limit elongation contains a value that could be associated with the heating characteristics [1]. This is the dynamic yield strength Y; which nature of the temperature dependence is known

$$Y = Y_0\left(1 - \frac{T}{T_m}\right), \tag{4}$$

where Y_0 is the yield strength under normal conditions; T is the current temperature; T_m is the melting temperature [15].

Relations (3) and (4) make it possible to establish the interrelationship between the values in natural conditions, when $\Delta T = 0$ preliminary heating is missing, and when it is present

$$Y_{\text{nat}} = Y_0\left(1 - \frac{T_{\text{nat}}}{T_m}\right), \quad Y_h = Y_0\left(1 - \frac{T_{\text{nat}} + \Delta T}{T_m}\right);$$

$$n_{\text{lim.h}} = n_{\text{lim.nat}}\left(\frac{Y_{\text{nat}}}{Y_{\text{h}}}\right)^{0.39} = n_{\text{lim.nat}}\left(\frac{1-\dfrac{T_{\text{nat}}}{T_{\text{m}}}}{1-\dfrac{T_{\text{nat}}+\Delta T}{T_{\text{m}}}}\right)^{0.39} =$$

$$= n_{\text{lim.nat}}\left(\frac{T_{\text{m}}-T_{\text{nat}}}{T_{\text{m}}-T_{\text{nat}}-\Delta T}\right)^{0.39}.$$

The last expression and the experimental formula (2) are leading to a dependence of the limit elongation coefficient n_{lim} not only on the initial gradient and radius, but also on the preliminary heating temperature:

$$n_{\text{lim.h}} = (A + B\dot{\varepsilon}_{z0}R_0)\left(\frac{T_{\text{m}}-T_{\text{nat}}}{T_{\text{m}}-T_{\text{nat}}-\Delta T}\right)^{0.39}.$$

This dependence was particularly used to account for the effect of heating on the jet dynamic plasticity.

The dynamic yield strength Y, not only affects the jet limit elongation n_{lim}, but also determines the jet behavior during its rotation and its probable centrifugal destruction. Main calculated relationships describing a rotating SC are briefly as follows [14].

Prior to the start of centrifugal destruction, the jet radial thinning parameters during its axial elongation are assumed to being the same as those of a non-rotating jet, i.e., SCJ element current elongation coefficient $n = l/l_0 = R_0^2/R^2 = 1+\dot{\varepsilon}_{z0}t$. It was assumed that the kinetic moment was maintained for any particle dm located at the R distance from the axis of rotation: $K_{dm} = \omega R^2 dm/2$. The law of a stretching jet untwisting from the initial angular velocity ω_0, was expressed by the following formula:

$$\omega = \omega_0\frac{R_0^2}{R^2} = \omega_0\frac{l_0R_0^2}{lR^2}\frac{l}{l_0} = \omega_0 n = \omega_0\left(1+\dot{\varepsilon}_{z0}t\right).$$

The moment of beginning of the rotating jet centrifugal destruction was determined by fulfillment of the critical condition:

$$\left(\frac{\rho\omega^2R^2}{Y_0}\right)_{\text{cr}} = C_{\text{cr}},$$

which is reduced by estimation results according to the previously considered models of high-gradient rods [13], where C_{cr} is a certain critical value of the current ratio between centrifugal and strength forces. Corresponding critical values of other parameters depend on the initial ratio of these forces and constitute:

critical radius

$$R_{\text{cr}} = R_0 \sqrt{\frac{\rho\omega_0^2 R_0^2}{Y_0} \frac{1}{C_{\text{cr}}}}; \tag{5}$$

critical angular untwisting speed

$$\omega_{\text{cr}} = \frac{C_{\text{cr}} Y_0}{\rho\omega_0 R_0^2};$$

critical elongation coefficient

$$n_{\text{cr}} = \frac{C_{\text{cr}} Y_0}{\rho\omega_0^2 R_0^2}.$$

The ratio of the jet element initial radius R_0, and of the critical radius R_{cr}, determines one or another element mode of operation, when it is elongated and untwisted. Algorithm for the corresponding calculation was presented in detail in works [13, 14]. Let us restrict here to a simple example, where the radius R_0 of the generated jet element is in the following relationship with the R_{cr} critical radius characteristic of the given element with its initial angular velocity ω_0 and material characteristics according to formula (5): $R_0 \le R_{\text{cr}}$. From (5), it consequently follows:

$$\frac{R_{\text{cr}}}{R_0} \ge 1, \quad \sqrt{\frac{\rho\omega_0^2 R_0^2}{Y_0} \frac{1}{C_{\text{cr}}}} \ge 1, \quad \frac{\rho\omega_0^2 R_0^2}{Y_0} \ge C_{\text{cr}},$$

i.e., the $R_0 \le R_{\text{cr}}$ condition corresponds to such a situation, when at the moment of the jet element generation the initial ratio of centrifugal and strength forces exceedthe critical value. Physically, this is the beginning of the element centrifugal destruction from the moment of its generation. At $R_0 \ge R_{\text{cr}}$, initial ratio of centrifugal and strength forces is not sufficient for this, i.e., the jet should stretch, and the ratio $\rho\omega^2 R^2 / Y_0$ should raise up to the value C_{cr}. In this case, jet centrifugal destruction could occur along the course of its elongation due to a decrease in the moment of inertia and the corresponding untwisting.

Algorithm for determining the disruptive action against a target by the SCJ elements, both partially destroyed and partially monolithic, is presented in Ref. [13, 14]. Lavrentiev's formula (1) was taken as the basis, and it was further modified

$$L = l_0\left[k_l + \left(1 - k_l\right)k_v\sqrt{\frac{\rho_{\mathrm{av}}}{\rho_{\mathrm{j0}}}}\right]\sqrt{\frac{\rho_{\mathrm{j0}}}{\rho_{\mathrm{t}}}}, \qquad (6)$$

where l_0 is the jet element initial length; k_l is the value characterizing part of the element length remaining and acting along the target; $1 - k_l$ is the coefficient of the jet efficient length reduction due to its centrifugal destruction at the uniform stretching stage; ρ_{av} is the average density of the centrifugally destructed jet element; ρ_{j0} is the SCJ material normal density; ρ_{t} is the target density.

The law of decompaction and alteration in time of the average density ρ_{av} of the jet centrifugally destroyed element has the form of the ratio between the following values:

$$\frac{\rho_{\mathrm{av}}}{\rho_{\mathrm{j0}}} = \frac{n_{\mathrm{cr}}}{n}\frac{R_{\mathrm{cr}}^2}{R^2} = \frac{n_{\mathrm{cr}}}{n}\frac{1}{1 + 0.2\omega_{\mathrm{cr}}^2\left(\Delta t\right)^2} = \frac{n_{\mathrm{cr}}}{n}\frac{1}{1 + 0.2\dfrac{\omega_0^2 n_{\mathrm{cr}}^2}{\dot{\varepsilon}_{z0}^2}\left(n - n_{\mathrm{cr}}\right)^2}.$$

In formula (6) k_v is the coefficient accounting for the effect of increasing the limit penetration velocity v_{lim} of a target by a decompaction jet. When the jet velocity is higher than the limit velocity at the given density, the coefficient $k_v = 1$, in the contrary case $k_v = 0$. As far as dependence of the limit penetration velocity v_{lim} on density is concerned, it is determined from the $\rho_{\mathrm{av}} v_{\mathrm{lim}}^2 = \rho_{\mathrm{j0}} v_{\mathrm{lim0}}^2$ pressures equality condition is exerted on a target by monolithic and decompaction jets and according to the target limit penetration velocity by a monolithic jet [1] ($v_{\mathrm{lim}\,0} \approx 2\cdot 10^3$ m/s for a copper jet and a high-strength steel target).

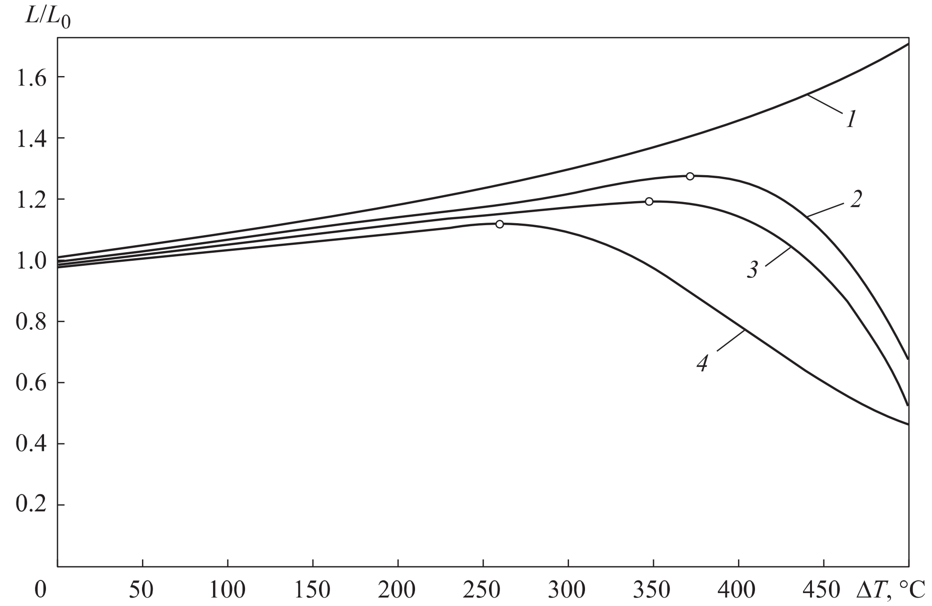
The dynamic yield stress Y, which is main strength characteristic require for calculating the rotational effects, was determined on the basis of experimental data using the so-called critical mass velocity, i.e., the difference in axial velocity between the adjacent separate jet elements [16]:

$$v_{\mathrm{cr}} = 0.65\sqrt{\frac{Y_{\mathrm{nat}}}{\rho_{\mathrm{j0}}}}.$$

The specific values v_{cr} were taken from the known experimental data [12, 17], according to which, copper of varying quality (M1 copper, M0 oxygen-free copper) could possess the following critical velocity values: 90, 110 and 130 m/s.

Results of thermal and centrifugal effects calculation. Results were obtained for a SC with a diameter of 72 mm [11]. Maximum possible rotation velocity was 30 s^{-1}. Natural temperature of the copper SC was 500 °C (average over the generally accepted range of values is 400–600 °C [1]). Figure demonstrates the effect of preliminary heating ΔT of the liner on the $\overline{L} = L/L_0$ jet penetrating ability for three values of the critical mass velocity v_{cr} (or dynamic yield strength Y). Curve *1* corresponds to the nonrotating charge, curves 2–4 correspond to the rotating charge with various v_{cr} and L_0 (penetration capacity of the nonrotating and unheated charge) values.

Optimum heating for maximum penetration exists for all the values v_{cr}. However, its contrast range increases with the growing jet material dynamic strength. Thus, for dynamic strength corresponding to the critical velocity difference of 90 m/s (curve *2* in the Figure), the optimal heating is 260 °C, and the SC penetration ability raises by about 10 % compared to the unheated SC. Such heating could quite remain a long time [1], and without any use of the explosive thermal insulator (phlegmatized octogen [7]).



Penetration ability dependence of nonrotating and rotating SC depending on SCL preliminary heating at various indicators of the jet material dynamic strength: *1* at ω = 0; *2–4* at ω = 30 s^{-1} (at v_{cr} = 90 (*2*), 110 (*3*) and 130 (*4*) m/s)

As the dynamic strength increases (v_{cr} = 110 m/s), the optimal initial heating continues, but shifts toward higher values (350 °C), and the maximum expected penetration effect reaches 20 % (curve *3* in the Figure). The observed extremum is not acute, and it appears at a slightly lower initial heating (≈ 330 °C), penetration capacity remains almost the same. In order to ensure such heating of the liner, a pulse action with a short admissible time period (~ 0.15 s) is required [8]. It is necessary to synchronize enabling thermal effects on the SCL; and such initial heating of the charge liner with octogen munition could still be carried out without additional thermal insulation of the explosive. Even greater values of dynamic strength ($v_{\text{cr}} = 130$ m/s) continue the indicated tendency (curve *4* in the Figure); when deriving the heating time period values from the optimal values region, it would be necessary to introduce thermal insulation of the SC explosive [8].

It should be mentioned that similar penetration capacity of nonrotating SC exposed to preliminary thermal effect on the liner was achieved earlier [6, 7].

On the whole, a positive answer could be given to the question of a possibility in principle to create a rotating SC with the liner exposed to preliminary thermal effect under conditions of the oppositely directed factors action. Factors of the SCJ temperature-strain additional elongation and its temperature-centrifugal destruction and decompaction turned out to be comparable in significance over the jet life time. One of them predominates at certain moments ensuring the SCL optimal initial heating and the SC penetration capacity with a local maximum.

Conclusion. When the SC initial rotation is missing, calculation predicts that the preliminary heating of the charge liner could significantly increase its penetration capacity.

Initial rotation frequency of 30 s^{-1} significantly reduces the penetration capacity of a charge with preliminary heated liner. According to any estimation of the jet material dynamic strength (Y = 0.17–0.36 GPa corresponds to v_{cr} = 90–130 m/s), there appears optimal preliminary heating that provides the maximum penetration capacity. This maximum penetration is by 10–12 % lower than penetration by a heated and nonrotating charge, but is by 15–28 % higher than penetration by an unheated and nonrotating charge. The rotation factor devalues the thermal factor effect, but does not completely overcome it.

When assessing dynamic strength within the specified range of values, optimal preliminary heating of the liner lies in the range of 260–375 °C. At the lower value of 260 °C, the octogen charge could remain in this state for a long time period. At the upper value of 375 °C, thermal effect on the charge should be only short-term, and the octogen charge should be thermally insulated.

REFERENCES

[1] Orlenko L.P., ed. Fizika vzryva. T. 2 [Explosion physics. Vol. 2]. Moscow, Fizmatlit Publ., 2002.

[2] Babkin A.V., Ladov S.V., Fedorov S.V. Behavior features of cumulative jets of composite powder liner in free flight. *Oboronnaya tekhnika*, 2007, no. 3-4, pp. 38–53 (in Russ.).

[3] Babkin A.V., Ladov S.V., Fedorov S.V. Analysis of influence of the sintered liner composition on the shaped-charge jet free flight behavior and its penetration capacity. *Proc. 25th Int. Symp. Ballistics*, 2010, vol. 2, pp. 959–966.

[4] Baskakov V.D., Zarubina O.V., Karnaukhov K.A., et al. Mathematical modelling of ideal flat jets impact. *Herald of the Bauman Moscow State Technical University, Series Natural Sciences*, 2016, no. 2 (65), pp. 79–90 (in Russ.).
DOI: https://doi.org/10.18698/1812-3368-2016-2-79-90

[5] Karnaukhov K.A., Baskakov V.D., Korenkov V.V., et al. Peculiarity of the shaped-charge liner collapse concerning the unevenness in its cross-section. *J. Phys.: Conf. Ser.*, 2017, vol. 894, no. 1, art. 012039.
DOI: https://doi.org/10.1088/1742-6596/894/1/012039

[6] Kolpakov V.I., Pletnev S.L. [The effect of liner pre-heating on efficiency of shaped charge]. *Tez. dokl. IV mezhdunar. konf. Lavrent'yevskie chteniya po matematike, mekhanike i fizike* [Abs. IV Int. Conf. Lavrentiev Readings on Mathematics, Mechanics and Physics]. Novosibirsk, IG SO RAS Publ., 1995, pp. 125 (in Russ.).

[7] Korenkov V.V., Obukhov A.S., Smelikov V.G. Increase of steel target penetration by charge with preliminary heated liner. *Dvoynye tekhnologii*, 1999, no. 4, pp. 53–54 (in Russ.).

[8] Babkin A.V., Ladov S.V., Fedorov S.V., et al. Maximum allowable parameters of pulsed thermal impact on ring systems with energetic material. *Oboronnaya tekhnika*, 2000, no. 1-2, pp. 35–40 (in Russ.).

[9] Babkin A.V., Bondarenko P.A., Fedorov S.V., et al. [Limitations of the possibilities for increasing penetration of shaped charge at pulsed heating its liner]. *Ekstremal'nye sostoyaniya veshchestva. Detonatsiya. Udarnye volny. Tr. mezhdunar. konf. III Kharitonovskie tematich. nauch. chteniya* [Extreme States of the Substance. Detonation. Shock Waves. Proc. Int. Conf. III Khariton Theme Readings]. Sarov, VNIIEF Publ., 2002, pp. 257–263 (in Russ.).

[10] Matrosov A.D., Babkin A.V., Ladov S.V., et al. Influence of magnetic fields on shaped charge performance. *Trans. PPPS 2001*, 2001, pp. 182–186.
DOI: https://doi.org/10.1109/PPPS.2001.1002023

[11] Selivanov V.V., ed. Boepripasy. T. 1 [Ammunition. Vol. 1]. Moscow, BMSTU Publ., 2016.

[12] Marinin V.M., Babkin A.V., Kolpakov V.I. Calculation technique of cumulative charge performance parameters. *Oboronnaya tekhnika*, 1995, no. 4, pp. 34–39 (in Russ.).

[13] Babkin A.V., Rassokha S.S., Ladov S.V. On centrifugal destruction of gradient rods. *Herald of the Bauman Moscow State Technical University, Series Mechanical Engineering*, 2010, no. S, pp. 182–195 (in Russ.).

[14] Babkin A.V., Rassokha S.S., Ladov S.V. Calculation method for functionality of the rotating shaped charges. *Oboronnaya tekhnika*, 2010, no. 1-2, pp. 23–30 (in Russ.).

[15] Johnson G.R., Cook W.H. A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures. *Proc. 7th Intern. Symp. Ballistics*. Hague, Netherlands, 1983.

[16] Babkin A.V., Ladov S.V., Marinin V.M., et al. Regularities of the stretching and plastic failure of metal shaped-charge jets. *J. Appl. Mech. Tech. Phys.*, 1999, vol. 40, iss. 4, pp. 571–580. DOI: https://doi.org/10.1007/BF02468430

[17] Svirskiy O.V., Vlasova M.A. Rating assessment of metals on the prospects of their use in cumulative charges liners. *Izvestiya RARAN*, 2006, no. 3 (48), pp. 83–88 (in Russ.).

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