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EFFECT OF INITIAL HEATING OF THE JET-FORMING LAYER OF SHAPED-CHARGE LINERS ON THE ULTIMATE ELONGATION OF JET ELEMENTS

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The functional dependence of the coefficient of ultimate elongation on the temperature of initial heating of the jet-forming layer of shaped-charge liners is obtained. It is established that heating of the shaped-charge liner material before initiation increases the ultimate elongation and, hence, the effectiveness of penetration of plastically fractured. high-gradient, shaped-charge jets.

The most widely used type of shaped charge (SC) is a brisant explosive charge of plane or axial symmetry in one of whose ends there is a cavity lined with a thin layer of metal, which is called the shaped-charge liner. Initiation of the explosive charge at the end opposite to the cavity leads to formation of detonation products, which act on the shaped-charge liner. As a result, the liner collapses to the symmetry axis and form high-gradient, metal, shaped-charge jets [1, 2].

High-gradient shaped-charge jets (SCJ) stretch in free flight because of the presence of a velocity gradient that appeared during jet formation. In the initial stage of existence, most of these jets undergo uniform stretching without concentrated deformation. At later times, stretching is localized in the regions of formation of necks. This results in plastic fracture of SCJ, i.e., breakup into a certain number of separate elements, whose length does not change in the subsequent process. This type of breakup is typical of copper, nickel, and niobium SCJ (see Fig. 1). The ability of an element of such SCJ to elongate without rupture is quantitatively estimated using the so-called coefficient of ultimate elongation, which is defined as the ratio of the total length of the jet element after rupture to its initial length. However, a different pattern of SCJ breakup is also possible. Thus, lead jets are characterized by uniform stretching followed by a sudden "volume" breakup, as shown in Fig. 1 for two sequential times. Jets formed from steel liners fracture mostly by "brittle" separation, with no formation of marked necks (see Fig. 1).

In the present paper, we consider the possibility of increasing the ultimate elongation of the elements of a plastically fractured metal jets by initial heating of the jet-forming layer of the shaped-charge liner.

For conical liners with a cone angle of 25–75°, the coefficient of ultimate elongation can be determined from the following empirical relation, which is given in [3]:

$$n = A + BR\,\mathrm{grad}\,V. \tag{1}$$

Here A and B are material constants determined from experiments, and R and $\mathrm{grad}\,V$ are the initial radius and velocity gradient along the SCJ. The coefficient of ultimate elongation can be determined using the theoretically calculated relation obtained by physicomathematical modeling of jet elongation and breakup within the framework of continuum mechanics [3]. These relation is approximated by the formula

$$n = 5.38(\rho R^2 \mathrm{grad}^2\, V/\sigma)^{0.39}, \tag{2}$$

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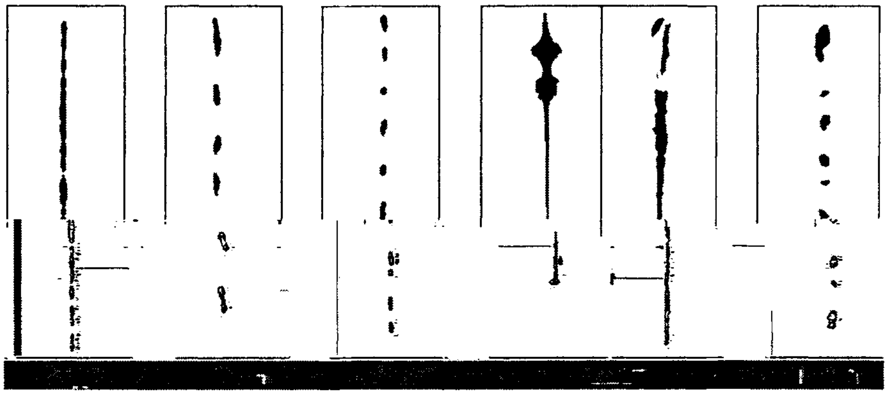

Fig. 1. Breakup of shaped-charge jets of various materials.

where ρ is the density of the material and σ is the dynamic yield point of the material under SCJ conditions.

The constants in relation (1) are obtained from experimental data for a particular material at the initial temperature of the shaped-charge liner equal to the ambient temperature. However, heating of the liner material before initiation of the explosive can lead to a considerable decrease in the strength of the SCJ material, which, according to Eq. (2), should increase the ability of the SCJ elements to elongate without rupture, other conditions being the same. To determine this effect, we establish the dependence of the coefficient of ultimate elongation of SCJ elements on the initial heating temperature of the jet-forming layer of shaped-charge liners using the modern concepts of deformation of metals and plastic fracture of SCJ.

We first determine the temperature and dynamic yield point of the SCJ material using the relation of [4] between the dynamic yield point of the material σ and the temperature of the material T:

$$\sigma = \sigma^*[1 - (\Delta T/\Delta T_m)^Z], \qquad 0 < \Delta T < \Delta T_m, \quad \Delta T = T - T_0, \quad \Delta T_m = T_m - T_0. \tag{3}$$

Here σ^* is the dynamic yield point of the material at $T_0 = 300$ K, ΔT is the resulting increment in the temperature of the material, T_m is the melting point of the material, and Z is a material constant. The first term in Eq. (3) describes the mechanical behavior of the medium at $T_0 = 300$ K. Generally, σ^* depends on the plastic strain intensity ε_i, which is the main characteristic of plastic shear strains, the plastic strain rate e_i, and other parameters:

$$\sigma^* = \sigma^*(\varepsilon_i, e_i, \ldots).$$

The second term in Eq. (3) defines the character of the temperature dependence of the yield point.

We assume that for any individual point M of the jet-forming layer of the liner under specified condition of compression an deformation of the SCJ, the dynamic yield point σ^* is known as a function of the plastic strain intensity ε_i at moderate values of the plastic strain rate $\langle e_i \rangle$ and pressure $\langle p \rangle$:

$$\sigma^*_M(\varepsilon_i) = \sigma^*_M(\varepsilon_i, \langle e_i \rangle, \langle p \rangle). \tag{4}$$

Here $\langle e_i \rangle$ and $\langle p \rangle$ are the average values of the plastic strain rate and pressure at an individual point M of the jet-forming material. Substituting (4) into Eq. (3), we obtain the dependence of the dynamic yield point for an individual point M of the liner material on the temperature increment ΔT during liner compression and SCJ formation:

$$\sigma_M(\varepsilon_i, \Delta T) = \sigma^*_M(\varepsilon_i)[1 - (\Delta T/\Delta T_m)^Z],$$
$$0 < \Delta T < \Delta T_m, \qquad \Delta T = T - T_0, \qquad \Delta T_m = T_m - T_0. \tag{5}$$

To determine the yield point σ_M under SCJ conditions, it is necessary to know the resulting temperature T_j of an individual point M of the material under SCJ conditions.

The major contribution to the heating of the jet metal is made by the initial heating, shock compression, and plastic deformation of the jet-forming material of the shaped-charge liner during liner compression and jet formation.

Approximately 90% of the energy expended in the plastic deformation of the metal goes into heating of the deformed material [5]. Because of the high strain rates, the time of deformation is so small that thermal conductivity can be ignored. Then, the formula for the increase in the specific work W_M expended in the plastic deformation of the jet-forming material of the liner at an individual point M is written as

$$dW_M = \rho c\, d(\Delta T_p)/0.9 = \sigma_M(\varepsilon_i)\, d\varepsilon_i, \tag{6}$$

where c is the specific heat of the material and ΔT_p is the temperature increment due to plastic strain. Substituting relation (5) into formula (6), we obtain

$$d(\Delta T_p) = \frac{0.9}{\rho c}\Big[1 - \Big(\frac{\Delta T_p + \Delta T_s + \Delta T_i}{\Delta T_m}\Big)^Z\Big]\sigma^*_M(\varepsilon_i)\, d\varepsilon_i,$$

$$0 < \Delta T_p + \Delta T_s + \Delta T_i < \Delta T_m, \qquad \Delta T_i = T_i - T_0, \qquad \Delta T_s = T_s - T_0,$$

where ΔT_i is the increment in temperature of the material due to the initial heating of the liner, T_i is the temperature of initial heating of the material, ΔT_s is the increment in temperature of the material due to shock compression, and T_s is the residual temperature of shock compression of the material. Separating the variables of the resulting differential equation and integrating, we obtain

$$\int\limits_0^{\Delta T_p} \frac{d(\Delta T_p)}{1 - [(\Delta T_p + \Delta T_s + \Delta T_i)/\Delta T_m]^Z} = \frac{0.9}{\rho c}\int\limits_0^{\varepsilon_i} \sigma^*_M(\varepsilon_i)\, d\varepsilon_i. \tag{7}$$

The data obtained in [4] for various metals show that for copper and some other materials, the parameter Z can be set equal to 1. Integrating the left side of equality (7), we arrive at the expression

$$\Delta T_p = (\Delta T_m - \Delta T_s - \Delta T_i)[1 - \exp(-J/\Delta T_m)], \qquad J = \frac{0.9}{\rho c}\int\limits_0^{\varepsilon_i} \sigma^*_M(\varepsilon_i)\, d\varepsilon_i. \tag{8}$$

For the specific conditions of liner compression and SCJ formation, we define the resulting temperature of the jet T_j at an individual point M of the metal with respect to T_0 as the sum of the increments due to plastic strain ΔT_p, shock compression ΔT_s, and the initial heating of the liner material ΔT_i:

$$T_j = \Delta T_p + \Delta T_s + \Delta T_i + T_0. \tag{9}$$

It should be noted that Eqs. (8) and (9) are similar to the equations of the analytical model of [5] for the SC temperature.

The temperature T_j is expressed in terms of the temperature T_j^0 of point M of the same material deformed under the same conditions but with no initial heating of the liner material. Below, the superscript 0 denotes the quantities for the case with no initial heating of the material.

Numerical results show that softening of the shaped-charge liner material does not have a significant effect on the kinematic characteristics of the deformation process, other conditions being the same, i.e., we can assume that $J = J^0$. Then, from inequality (8) it follows that

$$\Delta T_p/(\Delta T_m - \Delta T_s - \Delta T_i) = \Delta T_p^0/(\Delta T_m - \Delta T_s).$$

Using Eq. (9), we write

$$(T_j - \Delta T_s - \Delta T_i - T_0)/(\Delta T_m - \Delta T_s - \Delta T_i) = (T_j^0 - \Delta T_s - T_0)/(\Delta T_m - \Delta T_s).$$

Hence,

$$T_j = (T_j^0 - \Delta T_s - T_0)(\Delta T_m - \Delta T_s - \Delta T_i)/(\Delta T_m - \Delta T_s) + \Delta T_s + \Delta T_i + T_0. \tag{10}$$

From Eqs. (5) and (10), it is possible to determine the dynamic yield point of the material at an individual point M, assuming that the dependence $\sigma_M^*(\varepsilon_i)$ is known. Indeed,

$$\sigma_M = \sigma_M^*(\varepsilon_i)\{1 - [(T_j - T_0)/\Delta T_m]^Z\}.$$

Since the softening of the material has an insignificant effect on the value $\sigma_M^*(\varepsilon_i)$ given by Eq. (4), the above dependence leads to the relation

$$\sigma_M/\sigma_M^0 = \{1 - [(T_j - T_0)/\Delta T_m]^Z\}/\{1 - [(T_j^0 - T_0)/\Delta T_m]^Z\}.$$

Taking into account that for many metals, $Z \approx 1$, we have

$$\sigma_M/\sigma_M^0 = 1 - (T_i - T_0)/(T_m - T_s), \qquad 0 < (T_i - T_0)/(T_m - T_s) < 1.$$

As follows from the equation obtained, the dynamic yield point of the material at an individual point M can be treated as the average dynamic yield point of the material in the SCJ element, and T_i and T_s as the temperatures of initial heating and shock compression of the material of this element. As a result, we have

$$\langle\sigma\rangle/\langle\sigma^0\rangle = 1 - (T_i - T_0)/(T_m - T_s), \qquad 0 < (T_i - T_0)/(T_m - T_s) < 1, \tag{11}$$

where $\langle\sigma\rangle$ and $\langle\sigma^0\rangle$ are the average dynamic yield points of SCJ elements formed at $T_i > T_0$ and $T_i = T_0$, respectively.

Using relations (2) and (11) and ignoring the effect of the softening of the material on the kinematic characteristics of deformation of the shaped-charge liner material, we obtain the following ratio of the ultimate-elongation coefficient n of a SCJ element formed from the heated liner to the ultimate-elongation coefficient n^0 of an element formed under the same conditions but with no initial heating:

$$n/n^0 = (\langle\sigma\rangle/\langle\sigma^0\rangle)^{-0.39} = [1 - (T_i - T_0)/(T_m - T_s)]^{-0.39}, \quad 0 < (T_i - T_0)/(T_m - T_s) < 1.$$

This ratio makes it is possible to refine the ultimate-elongation coefficient which is determined, e.g., from the empirical formula (1). In this case, the dependence taking into account the initial heating of the liner jet-forming material has the form

$$n(T_i) = (A + BR\,\mathrm{grad}\,V)[1 - (T_i - T_0)/(T_m - T_s)]^{-0.39}, \quad 0 < (T_i - T_0)/(T_m - T_s) < 1, \tag{12}$$

where A and B are the material constants determined experimentally at the ambient temperature $T_0 = 300$ K, T_i is the temperature of initial heating of the jet-forming material, and T_m and T_s are the melting point and the residual temperature of shock compression of the jet-forming material of the shaped-charge liner.

Relation (12) takes into account the temperature of initial heating of the jet-forming material of shaped-charge liners in calculating the SC performance. With increase in the temperature of initial heating, the ultimate-elongation coefficient becomes larger. This makes it possible to use heating of shaped-charge liner materials before initiation of explosive charges to enhance the penetration capability of plastically fractures, high-gradient, metal jets.

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