8. C. M. Fowler, D. R. Peterson, R. S. Hawke, et al., "Railgun development for EOS research," in: Shock Waves in Condensed Matter, AIP Conf. Proc., N. Y. (1982).
9. R. L. Langlin, J. H. Gully, K. E. Nalty, and R. C. Zowarka, "System of the ultrahigh-velocity GEDI experiment," IEEE Trans. on Magnetics, MAG-22, No. 6 (1986).
10. G. A. Shvetsov, V. M. Titov, A. G. Anisimov, et al., "Railgun accelerators of macroparticles. Part I, General characteristics," in: Megagauss Technology and Pulsed Power Applications: Proc. Conf. Santa Fe, 1986, Plenum Press, New York—London (1987).
11. G. A. Shvetsov, V. M. Titov, A. G. Anisimov, et al., "Railgun accelerators of macroparticles. Part II, Experimental investigations," in: Megagauss Technology and Pulsed Power Applications: Proc. Conf. Santa Fe, 1986, Plenum Press, New York—London (1987).
12. G. A. Lyubimov and V. M. Rakhovskii, "The cathode spot of a vacuum arc," Usp. Fiz. Nauk, 125, No. 4 (1978).
13. G. A. Shvetsov, V. M. Titov, et al., "Investigation of the operation of a rail-gun accelerator of solid bodies with a feed from an explosive MHD generator," in: Superhigh Magnetic Field. Physics, Technology, Applications [in Russian], Nauka, Moscow (1984).

PENETRATION OF A STRONG BARRIER BY A SHAPED CHARGE JET

S. A. Kinelovskii and K. K. Maevskii

UDC 539.374

The hydrodynamic theory of detonation quite reliably describes the penetration of a shaped charge jet (SCJ) at sufficiently high penetration velocities. However, a marked difference between the theory and experiment [1-5] is seen with a reduction in velocity. This can be attributed to the actual effect of cohesive forces. An accurate empirical check of the hydrodynamic theory of penetration was made in [3] and a modification of this theory was proposed to consider the effect of the strength of the materials of the jet and the barrier (similar results were obtained independently by N. A. Zlatin). This modification consists of introducing "resistance" into the equation describing flow – the Bernoulli equation. It was noted in [4] that in the penetration of an object by an SCJ, the strength of the jet material need not be considered (a similar proposition was used in [5]). As a result, a formula is obtained which expresses the connection between the velocity V_j of the jet, the penetration velocity V_b, and the strength characteristic of the barrier material:

$$V_b = \frac{\lambda V_j}{\lambda^2 - 1}\left[\lambda - \sqrt{1 + (\lambda^2 - 1)\frac{2H_D}{\rho_j V_j^2}}\right], \quad V_b = \frac{1}{2} V_j\left(1 - \frac{2H_D}{\rho_j V_j^2}\right). \tag{1}$$

Here, H_D is the effective value of the dynamic hardness of the barrier material; $\lambda = \sqrt{\rho_j/\rho_b}$; ρ_j and ρ_b are the densities of the jet and the barrier. The second expression in (1) pertains to the case $\lambda = 1$. Equation (1) (below – model 1) represents one of the most widely used approaches to allowing for cohesive forces on the process of SCJ penetration.

In [4], yet another modification of the hydrodynamic theory was proposed. This modification leads to the formula (model 2)

$$V_b = \frac{\lambda}{1+\lambda} V_j \sqrt{1 - 2H_D/(\rho_j V_j^2)}. \tag{2}$$

Comparison of (1) and (2) shows that the SCJ ceases to penetrate the barrier at the same critical jet velocity ($V_j^* = \sqrt{2H_D/\rho_j}$) in both models, although the character of the effect of strength on the penetration process is described differently by each model. Penetration velocity begins to decrease at markedly lower jet velocities in model 1 than in model 2, i.e., the latter is characterized by a stronger "strength-engaging mechanism."

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 150-156, March-April, 1989. Original article submitted March 21, 1988; revision submitted May 11, 1988.

A method involving "recreation of the jet from the characteristics of its penetration into the barrier" was proposed in [6] for studying the process of SCJ penetration. The essence of this model is as follows. Let the dependence of penetration depth h(t) on time be known from experiments for the same given SCJ in barriers made of different materials. Using these data, we set the goal of recreating the SCJ — the velocity distribution along the jet — at a certain moment of time. For example, we might recreate the SCJ for the moment when the head of the jet touches the barrier (t = 0). If the models of motion and penetration of elements of the jet are both reliable in this case, then the recreated jet should be the same for all barriers. Conversely, the degree of agreement of the results of the recreation with each other will make it possible to judge the validity of the chosen models to a certain extent.

Let us examine the procedure of establishing the relation $V_j(x)$, where x is reckoned from the barrier counter to the jet. Empirical relations h(t) for each test are described piecewise analytically (such as by a second-degree polynomial). We then use differentiation to find the dependence of jet penetration velocity V_b on the depth h of the pierced barrier (similar to [3]). It is sufficient to conduct two or three experiments for each barrier material. Then the relations $V_b(h)$ are described piecewise analytically by the least-squares method for each barrier. Sections of approximation are chosen specifically for each barrier material, while the conditions of equality of the values of the functions and the first derivatives are imposed at the "joints" of the sections. The resulting approximate curves give an averaged representation of velocity $V_b(h)$ through the depth for each barrier material.

In the calculations, the motion and penetration of the jet are examined in a quasistatic approximation. In accordance with the latter, the motion and penetration of each element of the jet occurs as though the entire jet were organized as is the given element [2]. Also, it is assumed that each jet element moves toward the barrier without a change in its mean velocity and that a solid jet and a divided jet, consisting of the same elements, identically pierce the barrier.

Depending on the chosen model of penetration, the velocity of a jet element and its penetration velocity are connected by a certain relation

$$V_j = f(V_b). \tag{3}$$

The length of the jet element $\Delta\ell$ at the moment of penetration is connected with the increment of the depth of penetration Δh by the expression [2]

$$\Delta l = \frac{V_j - V_b}{V_b}\Delta h. \tag{4}$$

Equations (3) and (4) make it possible to find the velocity and length of jet elements that correspond to each value of h. To recreate the jet, we then need to find the length Δx of the given jet element at the chosen initial moment of time. These quantities are connected by the expression $\Delta\ell = \Delta x + [(x + h)/V_j]\Delta V_j$, which is a kinematic equation expressing the change in the length of an independent jet element whose ends have the velocity difference ΔV_j and which moves at the mean velocity V_j. It follows from this that the elongation n of each element of the jet is determined by the formula

$$\frac{1}{n} = \frac{\Delta x}{\Delta l} = 1 - \frac{x+h}{V_j}\frac{dV_j}{dV_b}\frac{dV_b}{dh}\frac{\Delta h}{\Delta l}. \tag{5}$$

To complete the procedure of recreation of the jet, we need to consider the fact that an axial velocity gradient may separate the jet into individual elements. As has been shown experimentally, the length of these elements undergoes almost no change after the separation [7, 8]. It is also known (see [1, 9], for example) that the maximum elongation n_* of the elements is different for different parts of the jet: whereas the limiting elongation is approximately equal to two for the leading parts of jets, it increases to 10-15 for the trailing parts. In the recreation of a jet in [6], the author used a model of constant jet elongation (n_* = const) and noted that the result of the recreation — or at least the qualitative character of the distribution $V_j(x)$ — is more heavily influenced by the choice of penetration model than by the choice of the model of jet motion. Nevertheless, we can use a model of motion of the jet elements which more closely reflects reality than does the constant elongation model: we will assume that the limiting permissible elongation n_* for our jet increases linearly along the length of the jet from the value of 2 in the head of the jet (x = 0) to, say, 10 at x = 40 mm (which corresponds roughly to the tail of the recreated

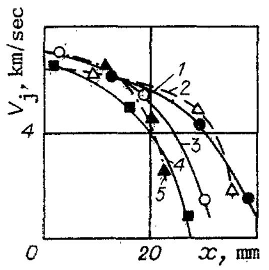

Fig. 1

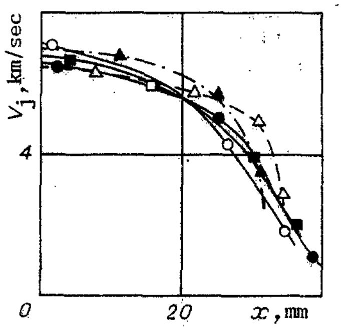

Fig. 2

jet). Thus, the initial length Δx of the jet element being recreated and its length Δℓ at the moment of penetration are connected by the equality

$$\Delta x = \frac{1}{n}\Delta l \quad (n < n_*), \qquad \Delta x = \frac{1}{n_*}\Delta l \quad (n \geqslant n_*). \tag{6}$$

Equations (3)-(6) make it possible to completely describe the procedure of recreating a jet at the moment of time when its head touches the barrier. It should be noted that the recreated jet is to a certain extent hypothetical, in light of the approximate nature of the models being used. Also, the jet will be hypothetical in the case when the charge is sufficiently close to the barrier; at the moment of time when the head of the jet touches the barrier, the tail elements of the jet may actually have yet to be formed.

Use of the above-described method allowed the author of [6] to observe that for an SCJ with a head velocity of 6-7 km/sec, there is an initial penetration section on which the compressibility of the barrier material must be considered in order for the results of the recreation to agree for different barriers; for the jet used in [6], the length of this section through the depth of the barrier was about 20 mm (the possibility of the existence of such a section was also noted in [1]). The results were analyzed in [6] with allowance for the compressibility of the barrier material and use of the hydrodynamic theory of penetration, i.e., when relation (3) has the form

$$V_j = \frac{1+\lambda}{\lambda} V_b. \tag{7}$$

This analysis made it possible to obtain agreement for a jet section about 15 mm long. Here, as already noted, the model of constant elongation was used for the motion of the jet elements.

Figure 1 shows similar results obtained from the more realistic model described above, with an increase in the limiting elongation of the elements toward the tail of the jet in accordance with a linear law. The different curves pertain to different barrier materials: 1) lead, total depth H_0 of penetration of the jet 120 mm; 2) aluminum, H_0 = 165 mm; 3) copper, H_0 = 105 mm; 4) steel, H_0 = 80 mm; 5) duralumin, H_0 = 110 mm. Here and below, the points are used only for clearer identification of the curves. Analysis of these results shows that with allowance for compressibility on the initial penetration section, satisfactory agreement is again obtained over a third of the recreated jet for different barrier materials. However, beginning with x = 15-18 mm, the results for materials of considerable strength deviate fairly quickly from the curves (1 and 2) which correspond to weaker materials (lead, aluminum). Thus, the next factor which must be considered by the penetration model is the strength of the barrier material.

Figure 2 shows results of the recreation of a jet by model 1 with allowance for the strength of the barrier material (the numbers of the curves are analogous to Fig. 1). It turned out in this case that for the best agreement between the results obtained it is necessary to take the following values for the dynamic hardness of the barrier material H_D (in GPa) in (1): lead, 0; aluminum, 0.4; copper, 4; steel, 7.5; duralumin, 6. Roughly the same results are obtained with the use of model 2. The resulting values of H_D are unrealistically large compared to those obtained in the penetration of monolithic projectiles, even if it is assumed that the effective value of the dynamic hardness of metals H_D is higher in the penetration of SCJ than in the penetration of a projectile. This result can actually be explained by the fact that approximately half the jet penetrates the barrier after it has separated into different elements. This was confirmed by photographs of a jet taken on a

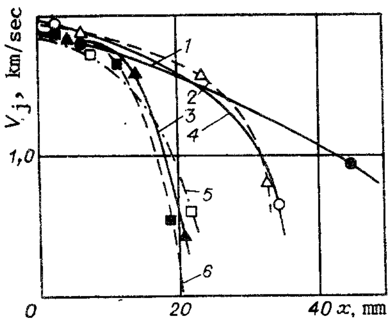

Fig. 3

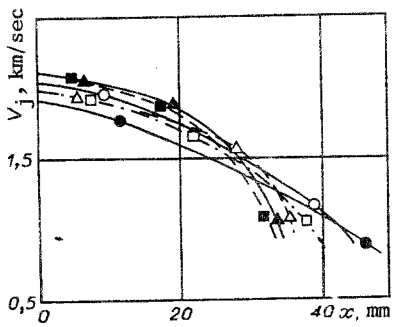

Fig. 4

pulse-type x-ray unit. Thus, the "divided jet effect" is in this case superimposed on the "strength effect," which leads to overestimation of the effect of strength on the penetration process. As was noted in [4], this is the reason for the overestimate in [10] of the velocity of a steel jet ($V_j \approx 4$ km/sec) at which the strength of the barrier material begins to affect the penetration of the jet into a barrier of mild steel.

After a jet separates into individual fragments, these fragments gradually diverge from one another due to their different velocities. Moreover, since the electrocontact method usually used to measure penetration velocity determines the mean velocity, then it becomes evident that the measured penetration velocity for a fragmented jet will, on the average, be less than the velocity of a continuous jet composed of these fragments. Another phenomenon associated with a "divided" jet is lateral dispersion of the jet elements and their contact with the walls of the already-pierced hole [1, 11]. The experiments conducted in [12] and described in [11], involving precision shaped charges (diameter 83.8 mm, 42-radius copper casing), are very illustrative in this regard. Here, the investigators determined the velocity of the jet elements for which penetration ceased. Whereas this velocity was 3.6 km/sec for a focal length of 6 diameters, it was 5.3 km/sec for a focus at 25 diameters (the tests were conducted with five focal lengths). It is evident that neither the first nor the last values of velocity associated with "cessation of penetration" are directly connected with the strength of the barrier.

Thus, in order to most fully study the effect of strength on the process of SCJ penetration, it is necessary to eliminate the effect of division of the jet in experiments. Shaped charges with hemispherical linings are very convenient in this regard. The jets obtained from such charges typically have a fairly low velocity, which is of interest from the viewpoint of studying the effect of strength on the penetration process. Also, due to the small velocity gradient and fairly large diameter, these jets remain intact for a sufficiently long period of time. In experiments we conducted, we used a shaped charge 48 mm in diameter with a hemispherical copper lining. The lining was 40 mm in diameter and had a wall thickness of 2 mm. The velocity of the head of the jet, measured by photographing it on a pulse-type x-ray unit, was 2-2.1 km/sec. The depth of penetration H_0 for different barriers was as follows: 1) lead, H_0 = 105 mm; 2) aluminum AMts, H_0 = 160 mm; 3) duralumin D16T, H_0 = 105 mm; 4) copper, H_0 = 100 mm; 5) steel St3, H_0 = 61 mm; 6) steel St. 30KhGSA, H_0 = 52 mm (the numbers correspond to the curves in Figs. 3 and 4). The mean values of H_0 and averaged relations $V_b(h)$ were obtained from the results of three tests for each barrier.

In connection with the low jet velocity in the given case, it turned out to be unnecessary to consider the compressibility of the barrier material on the initial penetration section. Figure 3 shows the results of recreation of the jet with the use of the hydrodynamic model of penetration (7). It is evident from this figure that about 15 mm of the jet is reproduced with a high degree of accuracy from the hydrodynamic model for all of the barrier materials investigated. For steels St3 and 30KhGSA and for duralumin, an appreciable deviation from the hydrodynamic theory is seen at a jet element velocity of about 1.75 km/sec, while the comparable figure for aluminum is approximately 1.25 km/sec. Now let us see the result of allowing for strength. Figure 4 shows the results of jet recreation with the use of penetration model 2 to describe the process. The best agreement for most of the jet is reached with the selection of the following values for the parameter H_D (in GPa), characterizing the strength of the barrier material: lead, 0; aluminum, 0.6; copper, 1; St3, 3; duralumin, 3.5; 30KhGSA, 4. Here, all of the curves depicting the velocity distribution of the jet lie in a band whose width is no greater than ±5% of the mean value. The agreement between the results is poorer for the tail of the jet, which is evidently connected with the division of this part of the flow. Qualitatively similar results are obtained with the use of model 1. The best agreement for most of the jet is achieved in this case with the use of the following values of H_D (in GPa): lead, 0; aluminum, 0.4; copper, 0.6; St3, 2; duralumin, 2; 30KhGAS, 3. However, the width of the band containing the curves here is ±10% of the mean value. It can be concluded from the aggregate of the results that, in a quantitative sense, model 2 describes the experimental results better on the whole than does model 1. On the other hand, analysis of the results shows that both models somewhat exaggerate the effect of strength on the penetration process for the leading part of the jet. For example, this is indicated by the increase in the scatter of the results at x = 0 in Fig. 4 compared to Fig. 3. It can be suggested on the basis of this that the mechanism of "strength engagement" is actually manifest to a greater extent than in model 2: for the barrier materials examined here, strength has almost no effect at a velocity of 2 km/sec for the elements of a copper jet, while the effect of strength is substantial at a velocity of about 1.5 km/sec for barriers of both steels and duralumin.

Thus, the results obtained here confirm the proposition [6] that the method of "recreation of a shaped charge jet," with the use of continuous jets, may prove to be a poor tool for studying the strength characteristics of materials at high deformation rates. In abstract terms, this method is qualitatively similar to Taylor's method (see [13], for example) of determining the dynamic yield point of metals with the penetration of a striker. The main difference is that one is not solving a direct problem involving the motion of the striker within the framework of the chosen penetration model. Instead, the inverse procedure is being performed — the jet is being recreated from the penetration characteristics within the framework of the chosen models of penetration and motion of the jet elements. It was found that in the case of penetration by shaped charge jets, the effective values of the dynamic hardness of the barriers turn out to be somewhat higher than in the case of penetration by monolithic strikers.

LITERATURE CITED

1. F. A. Baum, L. P. Orlenko, K. P. Stanyukovich, et al., Physics of Explosion [in Russian], Nauka, Moscow (1975).
2. M. A. Lavrent'ev and B. V. Shabat, Problems of Hydrodynamics and Their Mathematical Modeling [in Russian], Nauka, Moscow (1973).
3. R. J. Eichelberger, "Experimental test of the theory of penetration by metallic jets," J. Appl. Phys., 27, No. 1 (1956).
4. S. A. Kinelovskii and Yu. A. Trishin, "Physical aspects of detonation," Fiz. Goreniya Vzryva, No. 5 (1980).
5. N. A. Zlatin and A. A. Kozhushko, "Hydrodynamic model representations in the theory of the high-speed interaction of solids and the ranges of their application," Zh. Tekh. Fiz., 52, No. 2 (1982).
6. S. A. Kinelovskii, "Initial stage of penetration of a barrier by a shaped charge jet," Din. Sploshnoi Sredy, 48 (1980).
7. M. Van Thiel, M. Wilkins, and A. Mitchell, "Shaped charge sequencing," Int. J. Rock. Mech. Min. Sci., 12, No. 9 (1975).
8. J. Carleone, R. Jameson, and P. C. Chou, "The tip origin of a shaped charge jet," Propellants Explosives, 2, No. 6 (1977).
9. E. Hirsch, "A formula for the shaped charge jet breakup-time," Propellants Explosives, 4, No. 5 (1979).
10. M. A. Cook, "Mechanism of cratering in ultra-high-velocity impact," J. Appl. Phys., 30, No. 5 (1959).
11. E. Hirsch, "The natural spread and tumbling of the shaped charge jet segments," Propellants Explosives, 6, No. 4 (1981).
12. R. DiPersio, J. Simon, and A. B. Menedrino, "Penetration of shaped charge jets into metallic targets," BRL Report No. 1296, AD 478717.
13. M. A. Wilkins and M. Wynan, "Impact of a cylinder against a rigid barrier," Mekhanika, 3(139) (1973).