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Characteristics of quasi-liquid metal layer in the cumulative jet and barrier contact zone

According to the known experimental data on explosive metal processing, as well as the theoretical and experimental studies on the sintered metal powders, we estimated the minimum pressure and temperature values at which this layer and its thickness are formed. The study used a hypothetical model of forming a quasi-liquid metal layer between the leader of the cumulative jet, and a barrier at the time of its destruction.

Keywords: cumulative jet, destruction of barriers, boundary layer of metal.

The study [1] analyses the formation of the shaped charge penetrator after explosion of a shaped charge and compares analysis results with acquired experimental data. But this study does not propose any solution to the problem related to determination of characteristics of the quasi-liquid (viscous-flow) metal layer formed between the cumulative jet (CJ) and the barrier during their interaction. Moreover, there are no pre-conditions for solving the problems related to design of other assemblies intended for metal cutting and barrier protection against the impact of shaped charge devices.

Based on the fluid dynamic theory of destruction accepted by the authors in some studies [2–6], the state of the intermediate (boundary) layer between the CJ and the barrier in the barrier destruction zone is a liquid substance under high pressure, because the jet and the barrier are supposed to be liquid substances in the contact area. However, according to Y. K. Huang's data [7] indicating the state of metal exposed to super-high pressure, the crystal structure of the substance under such a load is not destructed. As per Y. K. Huang, metal destruction between crystals leads to the formation of an interlayer of microscopic thickness, and crystals slide along this layer relative to one another. This assumption is also supported by J. Hunt [8].

A. Tate [9] analyses three probable states of a high-velocity rod: a rod in the liquid state, a rod is a rigid body and the state in which penetration is interrupted.

W. Thompson [10] determines the thickness of the melted layer equal to around 1 mm in the zone where the body interacts with the barrier. Despite the differences in experiments at dynamic (high-velocity) and static loads applied to the object under test, these contradictory data are taken into account and partially used for creating a model, which implies that between the front (leading) part of the CJ and the barrier there is the substance interlayer that is part of a destructible barrier.

According to N. A. Gladkov's data [11], the plug removed from the barrier by the high-velocity penetrator shows no traces of melted contact surface between the penetrator and the barrier. The plug integrity indicates a smooth progress of the process from the zone where the CJ meets the barrier, and then into its solid mass. During stress release, the material of the destructible barrier is displaced from the cavity during the process of barrier destruction, while the substance may be in the liquid or even gaseous state [12]. However, according to studies [15, 16], explosion of a shaped charge with a spherical cavity does not cause CJ formation. The above phenomenon can be experimentally proven by the harness photo (see Fig. 3 in [17]) found after testing intended to cut a cylindrical shell (a linear shaped charge with a spherical cavity was used during tests). During stress release, the destructible barrier material is displaced from the cavity during the process of barrier destruction, while the substance may be in the liquid state, according to [12–14], or even in the gaseous state [12].

The intermediate (boundary) layer between the CJ and the barrier is conditionally referred to as the flow or quasi-liquid layer.

We assume that the process of barrier destruction includes the dynamic impact or the impact of the cumulative jet on the object and transition of the barrier material to the viscous-flow state. The dynamic process of CJ propagation through the barrier was analysed in [17].

The study objective is to determine characteristics of the viscous-flow metal layer between the cumulative jet and the barrier, which is formed during their interaction.

Using the data related to processes of metal nanopowder sintering (dependencies of the melting point on powder sizes and pressure values during their explosive sintering), as well as best practices regarding the control of the process of barrier destruction by the CJ allowed the authors to determine some characteristics of the metal in its viscous-flow state in the first approximation.

The study goal is to theoretically develop and determine the following characteristics, based on the known experimental data and best practices:

- model of the barrier destruction process in the contact zone between the barrier and the CJ;
- temperature of the intermediate (boundary, quasi-liquid) metal layer formed upon interaction between the CJ and the barrier in their contact zone;
- pressure acting on the metal layer;
- thickness of the boundary layer of quasi-liquid metal being formed.

Interaction between the CJ formed by explosion of a shaped explosive charge and the barrier is described by the fluid dynamic model proposed by Pokrovsky (1944) and Birkhoff (1948). According to the model, the barrier metal in the contact zone is in the flow state, while its flow process is regulated by the Bernoulli law. The study [18] proposes some corrected statements to the Pokrovsky – Birkhoff theory and highlights the need to run experiments in order to determine the barrier destruction rate and methods of CJ deceleration in the barrier solid, which allow to approach the solution to the problem of determining characteristics of this flowing metal interlayer at the time of its formation.

In case of impulse impact of the CJ and medium, the latter is heated under the action of high pressure. At that moment, melting of the surface metal layer can be observed in the contact zone. Transition of metals to the liquid (continuous flow) state under excess pressure, at which metals of Cu — Cu and Al — Al systems are welded at 2.5 and 0.65 GPa, respectively, as per D. Duval’s data [19]. R. Prümmer [20] specifies the data related to the shock wave pressure (2 GPa) at which low carbon steel powder is sintered.

According to J. Gering’s theoretical data [13] related to shock-wave heating of some metals, including data on Al, melting of the surface metal layer is observed when it is exposed to a shock wave under the pressure starting from 60 GPa, and the entire sample is completely molten under the pressure over 180 GPa.

According to Y. K. Huang’s calculations [7], if the velocity of a shock wave falling onto the metal sample surface is increased from 2940 to 4600 m/s, its surface will be additionally heated by 1815 K. The pressure of 80…150 GPa will be observed on the surface.

In the known published studies, pressure values that appeared during barrier destruction by the CJ were not measured due to the lack of appropriate equipment, and they were accepted, based on theoretical predictions, as the values within 10–100 GPa and higher. For this reason, the data given in [7, 13] and used herein are considered as estimated values.

Theoretically, the melting point of the boundary (quasi-liquid) metal layer largely depends on the pressure, by which the barrier destruction process is accompanied. This pressure is calculated by means of J. W. Gibbs’ energy equation (provided that the sample being analysed undergoes neither structural transformation μm nor chemical transformations and electromagnetic phenomena qU):

$$T_{\text{пл}} = E/S + PV/S - \sigma F/S, \qquad (1)$$

where P – pressure;
V – volume;
σ – liquid metal surface tension;
F – molten metal surface of the test sample;
S – entropy;
E – thermodynamic system energy.

Here we use the term “temperature” that is an intensive parameter in equation (1) regarding normal physical conditions; it is conditionally applied to the extremes observed during detonation; therefore, in order to estimate the melting point of the barrier metal, below we will specify the data on sintering of metal nanopowders exposed to super-high pressure. We should note that the nanoparticle melting point is way lower than the large-mass metal melting point.

Based on the above, we assume that the viscous-flow metal layer formed from the barrier and CJ (high-velocity penetrator) exposed to dynamic and thermal impact can be represented by the following model:

Metal feed

1. We assume that the leading part of the CJ in the zone of its contact with the barrier forms a thin quasi-liquid metal interlayer.
2. Quasi-liquid metal is displaced into the gap formed by the CJ itself and the inner surface of the chamber.
3. Once quasi-liquid metal reaches the outer surface of the barrier, its stress is released and the metal passes to the liquid or, probably, vapour state.

State of the CJ during barrier destruction

1. In the cross-section, the CJ consists of the quasi-liquid metal core (harness – high-velocity penetrator) being in the compressed state.
2. The core is located in an metal shell with the stress released.
3. There is a layer comprising a vapour or gaseous CJ component and gaseous explosion detonation products above the shell.

We consider quasi-liquid metal as a viscous substance with its elasticity beyond the limit as per [9, 23], in the continuous viscous-flow state.

In general, the CJ and accompanying explosive detonation products interact with the inner surface of the cavity inside the barrier, thus contributing to its expansion. We assume that until the last moment of barrier destruction, its parts do not move in any direction relative to one another due to the impact of excess pressure of explosive charge denotation products.

Before reaching the barrier, the CJ, depending on applicable explosive, may move at the velocity equal to the explosive detonation rate. Inside the barrier, if a linear shaped charge is used, this velocity is limited [17] (the performance of a linear charge with a spherical cavity was investigated), while the length of the CJ is reduced at the same rate. By all means, the quasi-liquid metal layer is displaced from the cavity at the rate equal the barrier destruction rate. Besides, it is assumed that the CJ moves inside the barrier and metal destruction products are displaced inside the cavity at the same velocity, until they are ejected from it.

There is contradictory data on the pressure formed by shock waves in powder-like media, at which metal surfaces (studied in [13, 19, 20]) start to melt. The difference between pressure values is greater than one order (see Table).

Therefore, the study [20] specifies higher (by one or two orders) pressure values to be reached in order to get metal surface layers melted.

With such ambiguous data of the experiment [19] and the theory [20], as compared in terms of pressure values, at which metal powders get melted, and due to the lack of other experimental data (except for [19]), let us take the study results [19] for estimating the state parameters in the quasi-liquid metal layer – between the barrier and high-velocity penetrator.

In the table, we summarized the known experimental data on shock-wave pressure values, at which surface melting for some metals can be observed.

In the recorded J. W. Gibbs equation (1) the third term is the surface energy of particles formed as a result of barrier destruction after the impact of a high-velocity penetrator. These particles form a quasi-liquid metal layer. According to the model that differs from the model proposed above and analysed in [20], powder sintering is caused by the impact of microcumulative jets formed between colliding particles under the shock wave impact. According to the theory (see equation (1)) and validation by experiment results, for example [24], the melting point (when the particle surface starts to melt) depends on the particle size.

According to the data [24, 25], the homologous melting point is ~0.5…0.6 T_{om} (melting point of lumpy metal in standard conditions). With other conditions being equal, metal nanopowder sintering can be observed, starting from this temperature. This may provide some extent of validation for the model proposed above.

Determined in [24, 25], the critical diameter (4.91 nm for Al) of nanoparticles, which are immediately melted within the entire volume, can be indirectly taken in the first approximation as the minimum thickness of the viscous-flow metal layer between the CJ tip and the barrier during destruction process.

According to the study [26], after explosion of a shaped charge with a 0.8 mm thick steel shell, the resulting CJ was 2 mm in diameter; the CJ thickness did not exceed the thickness of such a shell as per [27]. According to experiment data presented by the authors (measurements were conducted in several cross-sections of the cavity diameter), at the point where the CJ stopped, the thickness of the jet section which had directly destroyed an aluminium barrier, was not more than 0.4…0.5 mm, while the thickness of copper shells of linear shaped charges was 0.2 mm. In this respect, we can assume that the same process of viscous-flow material formation also takes place beyond the point of sphere contact along the line of CJ propagation, as well as on the side surface of the CJ due to stress release.

Assume that the end face of a high-velocity cylindrical penetrator in contact with the barrier is a hemisphere, and the mating recess (cavity) in the barrier also has a hemispherical shape (Figs. 1, 2).

Using the known mathematical apparatus for solving the biharmonic equation of function [23], which describes the process of plastic flow of material between two plates with radius r, being compressed at rate υ and maximum axial load f, we calculate thickness h of the quasi-liquid metal layer formed as a result of interaction between the cumulative jet and the barrier (see Fig. 2). The solution to the equation will be as follows:

$$h^3 = \frac{3\pi\mu\upsilon r^4}{4f}, \qquad (2)$$

where μ – dynamic viscosity coefficient of metal;

υ – CJ velocity in the barrier solid (velocity of plates moving relative to one another);

r – penetrator (CJ) working section surface radius;

f – CJ force acting on the barrier.

According to experimental data, the diameter of the cavity in the barrier (the area of contact with the CJ) is ~0.5 mm on average (see above, the measurement was conducted after testing). We assume that the cavity diameter is ~0.4 mm at the moment of barrier destruction. Pressure values for three above-listed metals are taken from the table (data from [19, 20] are marked with *) for the beginning of metal surface melting. The values of the dynamic viscosity coefficient of metals are taken from [28–30]. As a result, the formation of a quasi-liquid substance layer (calculated as per equation (2)) between the penetrator (CJ tip) and the barrier begins at $P_{\min}$ and $T_{\min}$ for the above-mentioned metals, while the layer thickness eventually reaches values within the range of 3.41 (Al), 3.56 (Cu) to 3.65 (Fe) µm. These figures exceed the critical diameter of particle for Al – 4.91 nm (see above). Of course, according to [20], the quasi-liquid metal volume will be reduced by

Experimental data on shock wave pressures acting on metal and causing its melting

Metal, GPa	Al	Fe	Au	Cd	Mg	Cu	Ni	Pb	Ti
Data [13]	$\frac{60}{90}$	$\frac{100\text{–}150}{200}$	$\frac{150}{160}$	$\frac{40}{46}$	–	$\frac{140}{>180}$	$\frac{>150}{–}$	$\frac{30}{35}$	$\frac{>100}{–}$
Data [19] and calculation as per *	*0.65*	3.1 3.1 (at T_{om} = 0.56)*	–	–	–	*2.5*	–	–	–

Note. Data specified by D. Duval in [19] are given in italics.
* – pressure value (for Fe) from [20] is recalculated using data from [24, 25] for the monolithic metal sample, where
T_{om} – melting point of monolithic sample

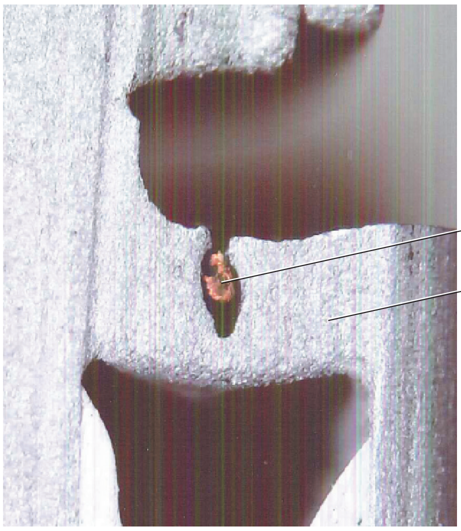

Fig. 1. Barrier cavity profile
after the CJ stops in the barrier:
1 – linear charge shell in the cavity;
2 – barrier

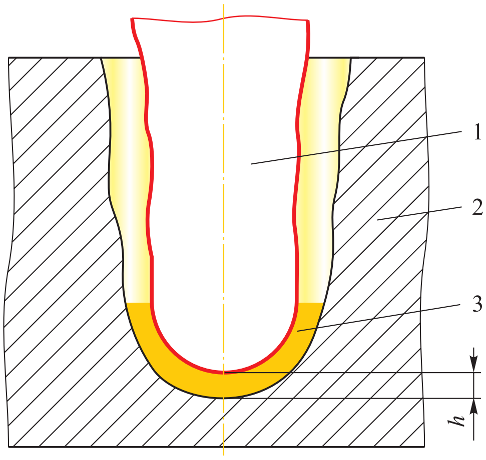

Fig. 2. Diagram of barrier destruction
by cumulative jet
1 – CJ; 2 – barrier; 3 – quasi-liquid metal
(viscous-flow medium)

more than ~15 % for Al and Fe upon stress release. If we use shock wave pressure values given in [13], at which surface melting of aluminium, copper and iron can be observed, these values will be lower by 4 times on average (they will be equal to around 1 μm) and are supposed to be too low for the range of pressures [19, 20], at which barrier destruction can be observed. We should note that in order to calculate the thickness of the viscous-flow metal layer between the CJ and the barrier, we considered surfaces of hemispheres instead of surfaces of spherical segments. That is why the obtained result is somewhat overestimated. If we assume that the CJ applies the pressure to the barrier, and the pressure value exceeds the value taken in the above examples by an order, the viscous-flow metal layer thickness will correspond to the calculated values obtained by the author in [13]. The barrier penetration velocity developed by the CJ is lower than the rate of detonation of the explosive that forms the cumulative jet, but the penetration velocity depends on the explosive charge power. The empirical velocity of aluminium barrier destruction (about 350 m/s) was obtained when cutting a thick-wall shell, the rear side of which was covered with a rubber-like material, unlike in [31]; this was done not to prevent fracture but to stop CJ propagation inside the barrier solid mass. The power (with account for the work of expanding detonation products) of a linear shaped charge with a spherical cavity was sufficient only for cutting a 4.5 mm thick shell.

We should note that, in addition to shock-wave pressure values observed during welding of pairs of metals such as AL – AL, Cu – Cu [19], V. S. Sedykh and N. N. Kazak [32] also specify data on low-carbon steel sheet welding (60 GPa) and assume that the metal flow in the welding zone has viscous behaviour. This assumption can be supported by experimental data presented by V. V. Pay and G. E. Kuzmin [33], who determined the barrier surface temperature in the area where it comes in contact with the CJ tip. The temperature value is approximately equal to the half of the melting point of the axisymmetrically shaped charge liner metal with a spherical cavity. According to L. P. Orlenko [34], barrier destruction begins due to the impact of the CJ formed after explosion of an axisymmetrically shaped charge, if the jet velocity exceeds the critical value – for the barrier and duraluminium liner the value is not less than 2200 m/s.

Conclusions

1. For the analysis, the process of barrier destruction can be viewed as a combination of two phases developing at velocities that differ from each other by an order:

– barrier destruction by shock wave;

– barrier destruction by the CJ with formation of a viscous-flow metal layer between the barrier and CJ.

2. In the first approximation, using indirect experimental data, we proposed the following: the barrier destruction model and the acceptable solution to the problem of calculation of minimum pressure and temperature parameters, which mark the initial phase of barrier destruction. The quasi-liquid metal layer is presented in the zone between the CJ and the barrier as a viscous substance with the elasticity beyond the limit.

3. The method intended for determining the metal layer characteristic can be viewed as the starting point for an in-depth analysis of the process of formation of quasi-liquid metal layer, for determining its physical characteristics and, probably, for developing alternative calculation methods.

4. Based on the known experimental data related to sintering of powder-like materials, we determined minimum values of pressures and temperatures, at which quasi-liquid metal is formed under the impact of the cumulative jet on the barrier. Under such pressures and temperatures, barrier destruction begins, in particular, if barriers are made of Cu, Al and Fe.

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Характеристики квазижидкого слоя металла в зоне контакта кумулятивной струи с преградой

На основании известных экспериментальных данных по взрывной обработке металлов, теоретических и экспериментальных работ по спеканию порошков металлов даны оценки минимальных значений величин давлений и температур, при которых образуется этот слой и его толщина. В исследовании использована гипотетическая модель образования квазижидкого слоя металла между лидером кумулятивной струи и преградой в момент разрушения последней.

Ключевые слова: кумулятивная струя, разрушение преграды, пограничный слой металла.

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