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Studies on Deformation Process, Flowing and Breaking Metal Linings at High Loading Speeds, Due to Explosion of the Cumulative Loads

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Abstract

Studying deeply the process of deformation, flowing and fracturing of the metal linings submitted to shock waves (at compression and stretching tension) generated by the explosion of cumulative loads, at high loading speeds rating 103- 104 m/s, the present study demonstrates that approximately 40 % of the height of the metal liner cone (of the cumulative funnel) cannot produce an effective jet for the desired penetration/ perforation of the armor. All this indicates that it may be possible to obtain the redesigning of the cumulative funnel tip to obtain the most effective use of the metal of which the lining is made.

Key words: *explosive cumulative charge, shock wave, cumulative effect, cumulative jet, metal armor perforation*

Introduction

Modeling the behavior of materials (of the lining and of the body and load) must explain the connection between the main tensions and deformations. With a calculation code (simulation) DYNA 2 D the elastic-plastic behavior patterns are integrated and allow consideration of the dynamic hardening and thermal annealing of materials.

It is known that the deformation tensor [2, 3, 4, 6] can be decomposed into a spherical tensor P and the stress deviator and so we have:

$$\begin{pmatrix} \sigma_1 00 \\ 0\sigma_2 0 \\ 00\sigma_3 \end{pmatrix} = \begin{pmatrix} \sigma_m 00 \\ 0\sigma_m 0 \\ 00\sigma_m \end{pmatrix} + \begin{pmatrix} \sigma_1' 00 \\ 0\sigma_2' 0 \\ 00\sigma_3' \end{pmatrix} \tag{1}$$

where: $\sigma_1, \sigma_2, \sigma_3$ are the main tensions

$$\sigma_m = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) = -p \tag{2}$$

$\sigma_1', \sigma_2', \sigma_3'$ are the components of the tension deviator

$$\sigma_1' + \sigma_2' + \sigma_3' = 0 \quad (3)$$

The behavior model contains a state equation describing the behavior of the spherical tensor and an elastic-plastic law to describe the deflector.

The equation of state used is Hugoniot - Gruneisen shock-type case adopted and connects the pressure (p), energy (E) and density (ρ) by through the following relation:

$\mu > 0$

$$p = \frac{\rho_0 C_0^2 \mu[(1+(1-\gamma_0/2)\mu)-(a/2)\mu^2]}{[1-(S-1)\mu]^2} + (\gamma_0 + a\mu)E \quad (4)$$

$\mu < 0$

$$p = \rho_0 C_0^2 \mu + (\gamma_0 + a\mu)E \quad (5)$$

where: ρ_0 is the initial density of the material: $\mu = \frac{\rho}{\rho_0}$ -1; C_0, S are the coefficients of linear relations between shock velocity (Us) and the particular speed Up, (Us = Co + SUP); Co is the speed of sound in the material; γ_0 is Gruneisen's coefficient; *a* is the first order correction of the γ_0.

In the elastic domain the load deflector Σ' and the deformation ε' link together by the help of Hooke's law:

$$\Sigma' = 2G\varepsilon' \quad (6)$$

where G is the transverse module of elasticity.

The limits of the elastic range are fixed by Huber-Mises' criterion which is expressed by the relation:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2 \le 2\sigma_y^2 \quad (7)$$

where σ_y is the limit of the plastic flow.

The tension deviator is calculated with equation (6) and whether the criterion (7) is satisfied this tension is accepted. If that is not supported, a plastic elongation is calculated and the components of the tension tensor are brought to such a value that Huber-Mises' equivalent tension shall be equal to flow tension σ_y.

The parameters of the law of behavior of the lining can be determined experimentally by: Taylor's test, compressive test in the Hopkinson bar, the ring expansion test [11].

The detonation of an explosive charge produces a detonation wave that moves towards lining, with the speed D (of the order of 8000 m/s). The action of the detonation products, which have a thermodynamic behavior, can be described by an equation of state [1, 5, 7]. For a 2D DYNA code calculation it is used a low JWL equation (Jones, Wilkins, Lee) of the following form:

$$p = A \cdot \left(1 - \frac{\omega}{R_1\left(V/V_O\right)}\right) \cdot e^{R_1 \cdot \left(V/V_0\right)} + B \cdot \left(1 - \frac{\omega}{R_2 \cdot \left(V/V_0\right)}\right) \cdot e^{R_2 \cdot \left(V/V_0\right)} + \frac{\omega \cdot E}{V/V_0} \quad (8)$$

where: p is the pressure; V is the volume of detonation products; V_O is the initial volume; E is the internal energy; *A*, *B*, R_1, R_2, ω are the coefficients of the law of JWL's.

The coefficients A, B, R_1, R_2, ω are determined experimentally for the type of explosive used.

Considering the moment when the explosive is completely detonated and almost totally accelerated, the action of the detonation products is replaced by the action of a pressure limit consisting of several pressure-time functions, as if there were radial divisions in the lining. The pressure-time function is of one of the type:

$$p = p_0 \, e^{-\alpha 1(t - t1)} \tag{9}$$

where: p is the pressure at time t; p_0 is the gas pressure detonated at a time t_0; α_1 is a constant.

The value of β can be calculated knowing the sizes for p and p_0 at times t and t_0 respectively.

It is known that high-speed jet tip may lead to the existence of large speed gradients. However, once the kinetic energy of the jet is large enough to exceed the forces of cohesion of the target material, high drilling speeds are not required. If the peak flow speeds are too high, the jet can create a shock wave in front of it that compresses and destroys the target material. This can increase the compressive strength of the target and makes it more difficult to pierce. The observations made refer to the very ductile targets at which the speeds of sound in the material that they are made of are very low.

It would be very useful in the manufacture of the cumulative funnels to determine what portion of the cumulative funnel the cumulative jet head is formed.

According to the theory of hydrodynamic flow it is considered that the top of the jet is formed from the top of the cone (of the metal lining), a hypothesis that cannot be not fully confirmed (J. Corleone, R. Jamenson and Pei Chi Chou) after the subsequent experiences made [5] .

The studies conducted show that the top portion of the liner with a cone angle of 42° is not effectively used. In fact, approximately 40% of the height of the cone, seen from the top down, does not produce an effective jet to produce the desired perforation, imposing an experimental and theoretical study of the dynamic behavior of the tip of the funnel. The research has been directed towards the possibility of redesigning the funnel tip for getting a more efficient use of the height of the funnel.

In order to analyze the experimental data, studies began to argue that the tip of the jet consists of a funnel conical tip. Later, it was assumed (Eichelberger) that the tip of the jet is not formed by the tip of the funnel but by a funnel element along the cone [9].

An analytical and experimental explanation was given does not explain to determine the origin of the peak, but it does not include the funnel acceleration and does not explain the mechanical reasons for the origin of the peak. For a steel funnel, studied by him, he placed the tip as the origin in a point at approximately 10-20% of the height measured from the tip of the cone of the funnel [9].

It has been determined through various experiments (Alisson, Vitali and DiPersio, Sicuou and Martin) that 40-50% of the height of the cone measured from the apex of the cone, a copper funnel, with a 42° cone angle, it is not used in the drilling process [10]. More recently, it was determined (Kiwan and Wisniewski) that approximately 15% of cone height measured from the tip to the base of the funnel is not used in the cumulative jet formation [11].

Experimental Results

Next, we will present the results of some experiments designed to track the origin of a cumulative jet, which will be compared with one-dimensional calculations to verify the theoretical assumptions concerning the speed, elongation and cumulative jet formation.

In theory, for determining the parameters of the cumulative jet, two criteria are included. A criterion is based on the alternative whether the collision of the jet elements is supersonic or subsonic. In some research it was established that very weak jets are produced when a supersonic collision occurs during the jet. However, supersonic collision occurs only in cargoes with cylindrical or conical linings with a very small apex angle (such as a cone angle of 20°). For a 42°cone angle at which the experiments were conducted, both two-dimensional and one-dimensional calculations have shown that the supersonic collision is not performed.

The other criterion is based on the existence of inverse velocity gradient of the jet elements at the top of the funnel. In the region near the tip of the cone, the distance between the position of the hopper walls and the axis of symmetry of the cone is not large enough that the elements shall be accelerated to their final speed of deformation. Therefore, a jet element in this area may be followed by an element having a higher speed, leading to interference or collision of the jet elements. Thus, the items in this area tend to accumulate and form a large particle.

Generally speaking, this assumption is consistent with the typical jet X-rays, where there can be noticed a relatively massive particle.

To study the effect of the reverse speed gradient, a series of experiments were conducted with standard BRL loads of 81.3mm in which portions of the funnel were filled with an inert material at various heights [7].

That inert material cancel the deformation of the area of the tip of the funnel, and from the radiographs of jets from these filled cones, the jet velocity can be measured and its particle's peak can be observed. These experiences help us to determine which area of the funnel contributes to the formation of the tip of the jet and which area provides a normal jet.

The results of these experiments are compared to the model of normal load without inert material.

The experimental program was carried out to determine the origin of the particles from the top of the jet observed by the radiography of the cumulative load jets.

To obtain concrete conclusions, a series of experiments were made using a standard BRL load 81.3mm as in Figure 1.

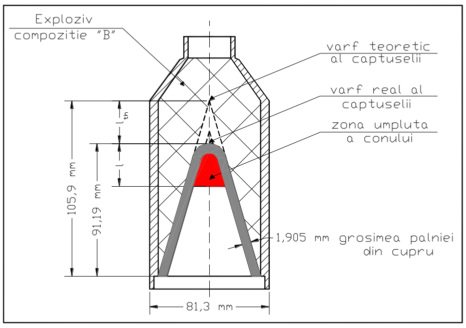

Fig.1. General scheme of a standard BRL load 81.3mm

In these experiments the tip of the funnel was filled at different heights (l), with Wood metal with a density of 9.9 g/cm^3, as shown in Figure 1. The six cases were considered corresponding to six different values of *l*, namely: *l* = 0; *l* = 12.7mm; *l* = 25.4mm; *l* = 38.1mm; *l* = 50.8mm; *l* = 63.5mm. The Wood metal was poured into funnels of the heights specified above, afterwards the funnels were placed in the cavities of the explosive charges. The complete manufacturing of the testing loads was performed at BALLISTIC RESEACH LABORATORIES (B.R.L.) [7]. In Figure 1 the theoretical and the geometric tip is indicated, that it is used as a basis for all comparisons. The ineffective height of the cone, $l + l_{th}$ is defined with respect to the theoretical height of the cone. Thus, for l = 12.7mm the inefficient height would be of 26% of the theoretical height of the cone.

The analysis of the results of the six cases has been done after observing the radiography of the three jets at distinct points in time.

The position of the peak ay each time is expressed as a distance from the theoretical tip of the cone.

The speed of the jet peak between the successive moments for each load separately, was calculated by dividing the distance travelled in certain intervals known. For cases with l = 0 and l = 12.7mm there can be noticed a relatively massive jet tip particle. In other cases l = 25.4mm, l = 38.1mm, l = 50.8mm, l = 63.5mm the tip particle has a size and shape similar to some conventional jet segments.

By measuring the size of the tip particle size in radiographs and considering their density as that of the original cone material (ρ_j = 8.9 g/cm^3), we could estimate the mass of the tip particle obtaining in these two cases given m_{tip} = 3.34g for it = 0 respectively m_{tip} = 2.38g for l = 12.7mm.

In the area near the tip of the cone, the elements of the funnel touch the axis of the cone before reaching their maximum speed of deformation. Therefore, an element having a jet speed of v_{j1} can be followed by an element having a higher jet speed that is:

$$v_{j2} > v_{j1} \tag{10}$$

This effect of the reverse gradient continues in the area near the top of the funnel to a distance from the real or theoretical peak at which we find the first jet element running at a speed lower than the speed of the tip particle combined (massive particle observed by X-rays).

Mathematically, it can be explained like this:

$$\overline{v_j}(x_{tip}) = \int_0^{x_{tip}} v_j(x)\frac{dm_i}{dx}dx \Big/ \int_0^{x_{tip}} \frac{dm_i}{dx}dx \tag{11}$$

where: x is the original axial position of the element on the cone; $v_j(x)$ is the speed of the first element of speed less than the combined particle's; x_{tip} is the point on the funnel where the reverse gradient stops and the effect of the normal jet is ensured; $\overline{v_j}(x_{tip})$ is the speed of the combined particle; dm_j / dx is the increase of the jet mass flow on the increase of the distance of funnel elements that get deformed as against the peak [7].

In order to do the calculations, the equation (11) is integrated numerically until a point x_{tip} is found as follows:

$$v_j(x_{tip}) \le \overline{v_j(x_{tip})} \tag{12}$$

Then this value of x_{tip} is considered the point on the funnel where the formation of the tip stops and starts the normal jet effect.

In conclusion, the determination of x_{tip} for each case of projected cumulative funnel helps us to know how far from the generator element is funnel element that forms the tip of the cumulative jet.

The fraction denominator of the equation (11) expresses the mass of the jet tip particle.

Conclusions

The studies presented, performed in specialized laboratories by American and Swedish researchers, can be starting points for research, design and manufacture of cumulative funnels.

Determining the ineffective portion of the cumulative cone height can lead to obtaining some more efficient funnels with lower technological expenses, as well as savings of scarce materials (copper, molybdenum, etc.).

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Studii privind procesul de deformare, curgere şi rupere a căptuşelilor metalice la viteze de încărcare foarte mari, urmare a exploziei încărcăturilor cumulative

Rezumat

Studiind în profunzime procesul de deformare, curgere şi rupere a căptuşelilor metalice supuse solicitărilor undelor de şoc (la compresiune şi întindere) generate la explozia încărcăturilor cumulative, la viteze de încărcare foarte mari, de ordinul $10^3 \div 10^4$ *m/s. Acest studiu demonstrează că aproximativ 40% din înălţimea conului căptuşelii metalice (a pâlniei cumulative) nu produce un jet eficient pentru penetrarea/perforarea dorită a blindajelor. Toate acestea indică că poate fi posibilă reproiectarea vârfului pâlniei cumulative pentru obţinerea utilizării cât mai eficiente a metalului din care este realizată această căptuşeală.*