Methodology for modeling of the jet formation process in linear sharped charges

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Introduction

Preparation of symmetrical cavity in an explosive charge e.g. of a conical shape (so called hollow charge) results in concentration of detonation energy of explosive products on that surface. The effect of directional action of the hollow charge can be significantly increased by lined the hollow cavity with a layer of solid material that has a shape of the cavity [1]. The layer is called liner and hollow charge with liner is called shaped charge. It consists of blasting explosive, insert and a case:

- high explosive has high detonation parameters such as: detonation velocity or quanity of gaseous prodcts [2]. Other selection criterion is, among others, its resistance to temperature that decides about application range of shaped charges
- an insert in the hollow cavity is made of solid material like ceramics, metal, glass (usually it is made of metal). Copper is the most popular material for the liner. Formerly the liner were obtained by the stamping process of sheet metal, but now are made from powders: of one metal (tin, copper, lead, tungsten), as well as properly prepared mixtures (aluminum, bismuth, zinc, cobalt, molybdenum, nickel, tantalum) that provide inserts of the appropriate density. This improves the perforation ability of the sharped charge
- a case is made of properly selected materials (zinc, aluminum, aluminum-zinc alloy and steel are the most frequently used materials) of such a shape that energy of explosive detonation forms a jet.

Table 1

Properties of most common high explosives used in shaped charges [2]

MW / Property	RDX $C_3H_6N_6O_6$	HMX $C_4H_8N_8O_8$	PETN $C_5H_8N_4O_{12}$	TNT $C_7H_5N_3O_6$
Molar mass, g/mol	222.10	296.2	316.10	227.10
Density, g/cm^3	1.76	1.9	1.70	1.60
Enthalpy of formation, kJ/kg	+301.40	+253.3	–1704.70	–295.30
Detonation heat, kJ/kg	6322	6197	6322	4564
Oxygen balance, %	–21.60	–21.6	–10.10	–73.90
Detonation velocity, m/s	8750	9100	8400	6900
Volume of detonation products, dm^3/kg	903	902	780	825

In the result of theoretical discussions and conducted tests, the structure of jet, mechanism of its generation [1, 3÷6], its penetration into uniform [7] as well as multi-layer [8] barrier, was determined. Pressure of detonation products gradually collapse and drives the liner. In the result of pressure growth, extrude of the material concentrated at the axis into two parts is observed, masses and velocities of which depend on parameters of the shaped charge. The first part is called 'jet' and the other is called 'slug'.

Jet – is elongated, strong heated stream of the liner material and it is produced inside its internal part. Face of the jet reaches velocity of 7÷10 km/s. Distribution of velocity along the jet can be considered as a linear one; it represents 10÷20% of liner mass.

Slug – contains greater part of the liner mass, it generates from external part of the liner, it moves relatively slowly (usually its velocity does not exceed 1 km/s),

In the result of shear effect, the jet and the liner rotate in opposite directions.

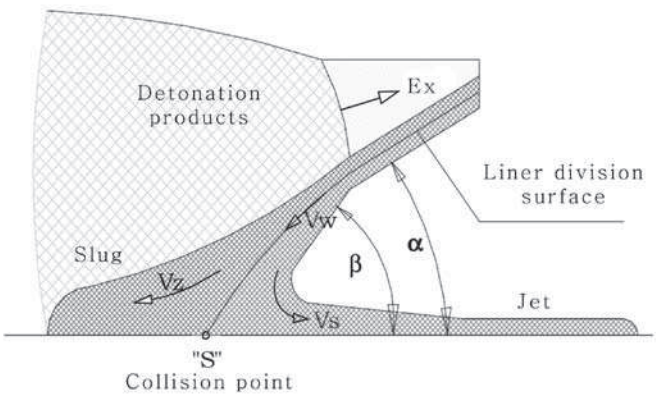

Fig.1. Process of formation of typical liner in the case of conical insert of angle 2α

The process of generation of jet from the shaped charge can also be modeled by use of proper mathematical models. Accumulation phenomenon belongs to fast dynamic interactions. Behavior of materials during simulation is described by the proper models and the model of elastic/viscous/plastic substance is the main model of metals in conditions of strong dynamic loads. Mathematical-and physical model is based on continuum mechanics equations (laws of conservation, Johnson-Cook or Steinberg-Guinan models; equations of state for solids as well as hydrodynamic model for explosives detonation products).

Model of linear shaped charge

The studies objective was the analysis and experimental verification of a model of linear shaped charge that could be used for determination of optimal distance of cumulative charge from the barrier. The model concerns one geometric system of the shaped charge but it has no limits as regards used materials of both explosive and insert and also the environment (usually air). The model can also be used for optimization of shaped charge depending on its application. Geometric model of linear shaped charge, which has a copper case, was created within the project, hexogen with teflon as phlegmatizer was used as blasting material in the cumulative charge. Shaped charge has the following dimensions:

- length - 250 mm
- external diameter - 26 mm

- insert thickness - 2.5 mm
- height of hollow cavity - 6 mm.

Steel sheet of thickness 20 mm was the barrier.

Then discretization of the model with a proper finite elements meshing was made, equations describing materials were selected and the standoff distanse was optimized. The model of linear cumulative charge was verified during field tests. The created model can be used for designing the next linear charges.

Standoff distanse

Standoff distance is a very important parameter as through it proper selection we can maximize energy transferred to the barrier by a jet minimizing at the same time the energy loss to environment increasing amount of possible work to be done. In practice Standoff distance is equal to caliber of the charge. However such a distance not always means maximal work done. It has to be admitted that both the liner geometry, the liner material as well as type of explosive have an impact on that parameter. Also the surrounding environment, in which the explosive is intended to be used, is significant. So, common belief that the standoff distance should be equal to its caliber is only rough approximation and it does not lead to maximization of energy transferred to the barrier by the jet. When selecting type of explosives we have to take into consideration conditions in which they will be used. It may happen that during detonation the liner material (in extreme case) will evaporate or break. With increase of opening angle of the liner the optimal distance is smaller. The major part of the liner goes to the jet and in the extreme case, where the opening angle of the liner is greater than 140°, all of its weight creates a jet known as explosively formed charge (EFP). In the result jet loses energy faster, what means less work to be done. When selecting the explosive material and shape of the liner we have to bear in mind the fact that it is a kind of transmitter and its design should provide the transfer of maximal part of explosion energy to the liner, while minimizing energy loss to the environment.

Description of behaviour

The following equations were used to describe behavior of explosives:

- High explosive burn – the model describes the explosive (till the generation of detonation products -DP), while DP's equation of state describes processes after detonation of the explosive. A fragment of reaction phase with the equation of state describing DP presents the quantity of energy released during detonation of the explosive. In the initial phase, time of reaction is calculated for each component by dividing the distance of initiation point to the component by detonation velocity. If there are multiple points of detonation defined, the point with the smallest distance from a given component is selected. If the value of transformation zone after calculations is greater than 1 (estimation accuracy), it is reduced to the value equal to 1. Usually a few steps are required to obtain a fraction of transformation zone equal to one. Uninitialized explosive can be modeled as a perfectly plastic elastic material [9].
- Johnson-Cook – this is an empirical equation of the following form used to describe metals:

$$\sigma_y = (A+B\cdot\varepsilon^{-n}) \cdot (1+C \cdot In\varepsilon^{*}) \cdot (1-T^{*m}) \qquad (1)$$

where:

$$T^{*} =^{m} \frac{T-T_r}{T_m-T_r} \qquad (2)$$

where:

A, B, C, n, m – material parameters in Johnson- Cook equation

T – temperature

T_m – melting point

T_r – ambient temperature

ε – internal energy

ε^{*} – velocity of deformation

$\bar{\varepsilon}$ – plastic deformations

σ_y –plastic stress

- Null – the equation is useful for modeling in the conditions when elements it describes connect together just after the zone defined by the model of explosive. A model of that explosive is not used to remove the elements from calculation but it can be used for explosives whose strength can be neglected. The model was used to describe the environment surrounding the cumulative charge and the barrier. This is an equation of state in which a high number of constants is used to improve compatibility between real values and those obtained from modeling. That polynomial has the following form:

$$p = C_0+C_1\cdot\mu + C_2+\cdot\mu^2 + C_3+\cdot\mu^3 + (C_4+C_5\cdot\mu + C_6\cdot\mu^2)\cdot\varepsilon \qquad (3)$$

where:

$$\mu = \frac{1}{V_{rel}} - 1 \qquad (4)$$

where:

ε – internal energy

$C_0, C_1, C_2, C_3, C_4, C_5, C_6$ – constants of linear polynomial equation

- equation of state JWL (Jones-Wilkins-Lee); The authors approximated the isentrope coming from point C-J with the following relationship:

$$p = A\cdot exp^{-R_1\cdot V} + B\cdot exp^{-R_2\cdot V}\ C\cdot V^{-(1+\omega)} \qquad (5)$$

where:

$$\bar{V} = \frac{e}{e_0} \qquad (6)$$

ρ – specific density

A, B, R_1, R_2, ω, are determined empirically. The so called expansion cylinder test is one of the methods for their determination. In that method an areola of cylindrical explosive is driven. The process is observed and recorded using quick change methods for recording quick change processes. Recorded results are compared with the results of computer simulation, which leads to determination of the above mentioned constants. The constants are selected in such a way as to adjust the experimental results with the simulation results [9].

It has been assumed that Grüneisen constant $\Gamma(\varrho)$ is constant in the entire range of pressure changes and it is equal to ω. The above equation is usually presented in the following form:

$$p = A\cdot\left(\frac{\omega}{R_1\cdot V}\right)\cdot e^{-R_1\cdot V} + B\cdot\left(A-\frac{\omega}{R_2\cdot V}\right)\cdot e^{-R_1\cdot V} + \frac{\omega\cdot\varepsilon}{V} \qquad (7)$$

Equations (5), (7) conform with a good accuracy to experimental results for the value $\frac{e_0}{e} \leq 7$. In the case of testing continuation of DP decompression process in the range $\frac{e_0}{e} > 7$additional orrection to JWL equation should be used or other equation of state should be applied.

Additionally an initiation-detonation point was put in the model to initiate explosive detonation.

Results of tests

The following equations were used to describe accumulation [9]:

- for description of explosive and detonation products (DP): Jones-Wilkins-Lee equation of state, high explosive burn equation
- for description of metal: linear polynomial equation of state, Johnson-Cook equation
- for description of air: linear polynomial equation of state, Null equation.

The equations are available in literature [5, 9] and in *LS-Dyna software library.*

Additionally an initiation-detonation point was put in the model to initiate explosive detonation.

Preparation of finite elements mesh is the most important and also the most labor consuming stage of simulation of the given phenomenon. Geometry discretization consists in dividing it into finite elements having finite dimensions. Interactions among the elements are determined in the elements' nods and the shape function is used to describe the relationship between node quantities of a given element; the task of this function is to recreate physical properties of a given element. Selection of the number of nodes and the shape function are such as to recreate the tested phenomenon in the most precise way. Meshing structure is a kind of compromise between the expected accuracy and the analysis cost. Size of the mesh elements should be selected in such a way as to make finite elements mesh possibly loose with good results. The model used for simulation should correspond to a real one as far as it is required; if possible, the following simplification should be used:

- geometric – in points where high accuracy of calculations is not required
- use of symmetry plane – at the same time it has to be geometric symmetry, symmetry of properties of used materials as well as load symmetry of.

Additional increase of calculation accuracy can be achieved by use of the so called sub-modeling. The accuracy of the model discretization has a direct impact on both the precision of the calculations and their speed.

It should be noted that there can be defects in the mesh, which would have a direct impact on analysis results and sometimes they can make analysis impossible. Properly selected center geometry enabled constructing of a regular hexagonal mesh. In addition, knowledge of the simulated phenomenon enabled to make the mesh denser in the area of interest and looser in other areas. Due to such a procedure, accuracy of calculations was increased with only a small increase of computer calculation power parameters. Then the mesh was processed to eliminate any deficiencies that could lead to calculation errors. The mesh for 2D simulations in LS-Dyna software should have a minimum thickness of 1 element to enable calculations, so 2D discretization is *de facto* 3D. Nevertheless, the set boundary conditions make the simulation regarded as two-dimensional. The meshes built for simulation of accumulation phenomenon contain only regular hexagonal solid elements, the shape of which has an impact on the accuracy of results.

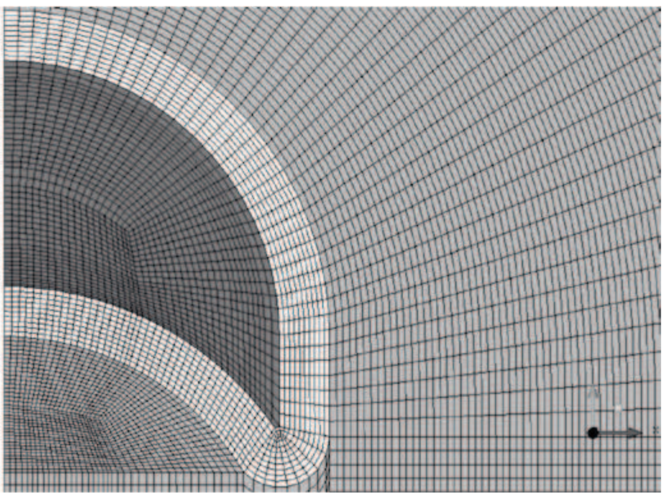

Fig. 2. Photo of the mesh built for shaped charge testing system

By use of simulation of accumulation phenomenon it is possible to determine the optimal standoff distance (for each cumulative charge). During the simulation of accumulation phenomenon the standoff distance is optimized not only as regards the liner opening angle but also as regards the materials used, geometry and environment conditions. In Figure 3 the process of creation of a jet for tested shaped charges is presented.

Fig. 3. The process of jet formation from the pressed shaped charge – time interval $3.00 \cdot 10^{-3}$ ms

Table 2

Parameters of jet formation from the pressed shaped charge, case material: copper

step		1	2	3	4	5	6
$t \cdot 10^{-3}$, ms		0.00	3.60	7.20	10.80	14.40	18.00
h, mm	ŁKL-P	26.00	24.48	20.07	14.92	9.26	4.12

From Table 2 it results that the jet gets proper shape after $18 \cdot 10^{-3}$ ms. The field tests consisted in constructing of the test stand, which included the tested shaped charge placed on standoff distances placed on a set distance from the floor. The height of distances was selected in such a way that the top of liners was in a distance equal to the charge caliber (Fig. 4). In the case of these tests the standoff distance was 26 mm. The barrier made of steel plates was placed in some distance from the floor to eliminate impact of reflected wave on the final cutting effect. The explosive was initiated by an ERG detonator.

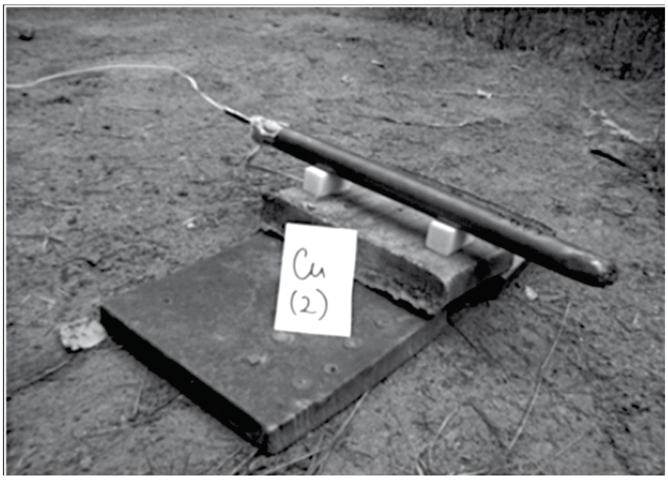

Fig. 4. Test stand

Fig. 5. View of the test stand after explosive detonation

Fig. 6. Effect of jet action

Summary

LS-Dyna software as well as equations available in the literature was used to develop a model of the accumulation phenomenon of elongated explosive charge. Usually the modeling process is faster and cheaper than field tests and, first of all, it is safer. As results from the presented investigations, it is possible to develop geometric models recreating behavior of the explosive shaped charge; thus, it is possible to determine the optimal distance of the charge from the barrier standoff distance. The modeling enables visualization of the jet at each stage of its life as well as determining parameters of the jet (pressure, energy, density, stresses and velocity). This allows for getting to know its nature and design of good real systems. The field tests confirmed results obtained from simulations on models. The models can be used for optimization of explosive shaped charges depending on their applications.

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