Numerical simulation of explosively driven aluminum flyer acceleration

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Abstract

The acceleration of explosively driven aluminum flyer was successfully simulated using LS-DYNA code. The properties of the explosive (A-IX-1, RDX/binder 95/5) was completely calculated by Explo5 program (detonation velocity and pressure, JWL parameters for the expansion isentrope).The results were compared to the experimentally obtained velocity profile, measured previously with PDV. The both curves agree by shape, velocity values at the individual steps and their duration. Also the terminal velocities agree very well.

Keywords: numerical simulation, LS-DYNA, acceleration, flyer, Explo5

1 Introduction

Flyer plate experiments are used in the field of shock physics for determination of material properties under shock loading [1-3]. Stationary plate is subjected to shock loading and the rear surface velocity is measured. The loading is often achieved by impacting projectile and the state of the studied material is determined from known impact velocity and projectile properties.

In the field of explosives, metal plate is placed in contact with the explosive charge and acceleration caused by interaction of the flyer surface with the detonation products is measured. Two important pieces of information can be obtained from such test. Firstly the velocity profile acquired when using known explosive can be used to characterize the velocity that the metal reaches at particular distance. This is problem was first addressed by Gurney [4-6] during WWII but is of particular interest in ammunition construction or explosive welding. Secondly using known metal flyer enables determination of explosive properties. In such experiment velocity of the free surface (or apparent velocity measured through impedance matching window) corresponds to the shock amplitude generated by the explosive on the interface between the detonation products and the accelerated metal. Knowing the metal properties one can determine properties such as particle velocity or detonation pressure of the explosive under study [7].

Determination of the rear surface velocity can be done by various methods including PDV (Photonic Doppler Velocimetry) [8, 9], VISAR (Velocity Interferometry System for Any Reflector) [10], Fabry-Perot interferometry [11], contact pins [12] or high speed imaging by streak cameras [1, 2]. All of these methods provide results, however with significant difference in time and spatial resolution, ease of measurement preparation or price. PDV and VISAR are commonly used today.

Experimental determination of the velocity profile is possible, however requires preparation of the explosive and pressing it to a reasonably sized charge to achieve stable detonation parameters. In the early stages of development of new substances it is desirable to have ability to simulate the flyer acceleration numerically, e.g. using finite element codes. One of these codes, widely used for the simulation of detonation, is LS-DYNA. To conduct such numerical calculation it is necessary to describe the explosive and its expansion isentrope which is not known for new substances and must be calculated using for example Explo5 code. Together with generally known properties of the flyer and also the behavior of surrounding air acceleration profile can be determined.

In this contribution we demonstrate the use of Explo5 for determination of explosive properties of composition containing 95 percent of RDX and 5 percent of nonexplosive binder and the use of the calculated detonation parameters in determination of an aluminum flyer velocity profile. The calculated results are then compared to experimental ones demonstrating predictive capability of this approach.

2 Experiment

The experiment was in detail described elsewhere [13], only the brief description follows. An aluminum disc was accelerated by the explosive charge with a diameter 40 mm and length 40 mm (A-IX-1, 95% of RDX, 3% ceresin, 2% stearin, density 1.66 $g \cdot cm^{-3}$). An aluminum disc (40 mm in diameter, nominally 1 mm thick) was placed on the upper side of the charge. The real thickness of the aluminum flyer was 0.96 mm. The charge was initiated from the bottom with a standard electric blasting cup which was centered using a polypropylene guide ring in the a 40 g booster charge of Semtex 1A - plastic bonded explosive based on pentaerythritol tetranitrate (PETN). The booster charge served more as a detonator holder than a real booster charge and therefore was omitted from the model. The velocity of the disc was measured using single channel PDV system.

3 Thermochemical calculation

Calculation of detonation parameters was conducted using Explo5 V6.02 thermochemical code [14]. The empirical Becker-Kistiakowsky-Wilson (BKW) equation of state was used for detonation products. The BKWG-S set of parameters ($\alpha = 0.5$; $\beta = 0.38$; $\kappa = 9.32$; $\theta = 4120$) was selected which is nearly the same as the BKWN set used in [15] which fits well for high explosives in a wide range of densities.

The input parameters corresponded to the ones defined in experimental section. The explosive composition was defined as 95% of RDX, 3% of wax and 2% of stearin, because the ceresin is not present in the compound database. The initial density was set to 1.66 $g \cdot cm^{-3}$. The equilibrium freezing temperature was set to 1800 K.

4 LS-DYNA simulation

The acceleration of the aluminum disc was simulated using of LS-DYNA code [16]. The entire experiment, as described in section 2, was modeled using ALE (Arbitrary Lagrangian Eulerian) approach. Due to the symmetry, geometry was simplified to 2D (axial symmetry) to reduce the number of elements and nodes. Both explosive and air were modeled as an Euler type materials. Aluminum was modeled as Lagrange type material. The part of a model "bellow" the Lagrangian part was modeled as a vacuum (Euler). The interaction of Euler and Lagrange parts of the model was ensured by the *CONSTRAINED_LAGRANGE_IN_SOLID card.

4.1 Model

The axisymmetric model consists of over 46,000 shell elements and is displayed in figure 1. The element sizes are 0.25 mm in an Eulerian part and 0.083 mm in a Lagrangian part.

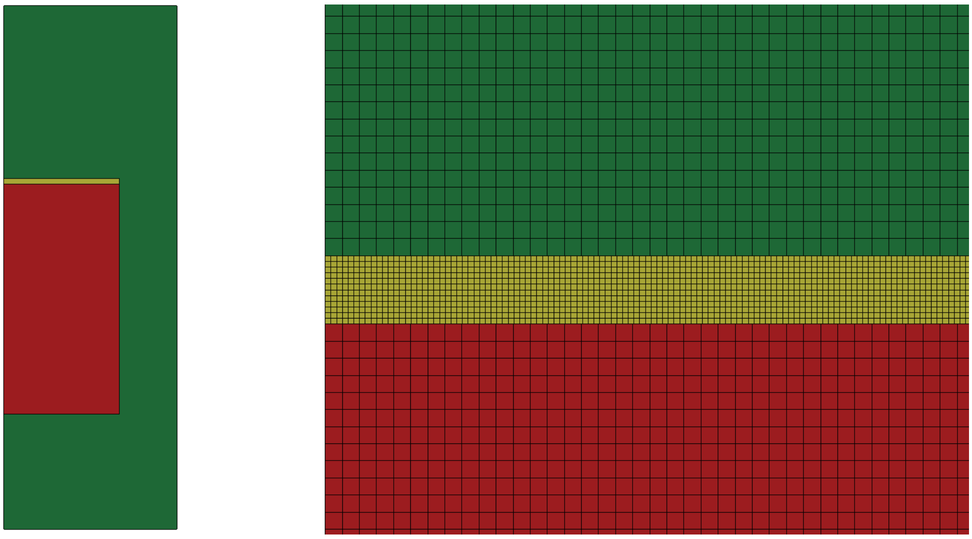

Figure 1: An axisymmetric 2D FEM model. Overall view of the model is on the left side and a detail is on the right side. There are Eulerian parts (green air and red explosive, vacuum “bellow” the aluminum is not shown) and one Lagrangian part - yellow aluminum.

4.2 Material parameters

The properties of the explosive (A-IX-1, RDX/ceresin/stearin 95/3/2) were obtained from the Explo5 code and the explosive was modeled as a *MAT_HIGH_EXPLOSIVE_BURN with *EOS_JWL – equation (1):

$$P = A\left(1-\frac{\omega}{R_1 V}\right)\exp^{-R_1 V} + B\left(1-\frac{\omega}{R_2 V}\right)\exp^{-R_2 V} + \frac{\omega E_0}{V} \quad (1)$$

where P is pressure, V is relative volume and A, B, R_1, R_2, ω and E_0 are JWL constants calculated by the EXPLO 5 thermochemical code. The properties of the explosive, as used as an input for LS-DYNA simulation, are listed in table 1.

Table 1: The calculated properties of A-IX-1.

d [kg·m^{-3}]	D [m·s^{-1}]	P_{CJ} [GPa]
1660	8258	27.35

JWL parameters

A [GPa]	B [GPa]	R_1 [-]	R_2 [-]	ω [-]	E_0 [GPa]
887.8658	23.82617	5.18	1.60	0.452	9.19

The air was modeled as an ideal gas (*MAT_NULL with the density 1.225 kg·m^{-3} and *EOS_LINEAR_POLYNOMIAL, $C_0 = C_1 = C_2 = C_3 = C_6 = 0$ and $C_4 = C_5 = 0.400$) and the vacuum was modeled as *MAT_VACUUM, with the density 1.225 kg·m^{-3}. The linear polynomial equation of state follows:

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E \quad (2)$$

where P is pressure, μ is the ratio of current density to initial density, E is internal energy and C_0-C_6 are constants.

The aluminum was described by Johnson-Cook equation (*MAT_JOHNSON_COOK) and with linear polynomial EOS (*EOS_LINEAR_POLYNOMIAL), according to [17]. The Johnson-Cook model expresses the flow stress σ_Y as:

$$\sigma_Y = [A + B\bar{\varepsilon}^{pN}](1 + C\ln\dot{\varepsilon})[1 - (T_H)^M] \quad (3)$$

where $\bar{\varepsilon}^p$ is effective plastic strain, $\dot{\varepsilon} = \dot{\bar{\varepsilon}}^p / \dot{\varepsilon}_0$ ($\dot{\varepsilon}_0$ is used to determine A), T_H is homologous temperature $T_H = (T - T_R)/(T_M - T_R)$ (T is temperature, T_M is melting temperature and T_R is reference temperature when determining A), $\Delta T = \frac{1}{d C_P}\int \sigma \mathrm{d}\bar{\varepsilon}^p$ (d is density and C_P is specific heat), and finally A, B, N, C and M are constants.

In addition there is an element failure criterion, that allows for the immediate reduction in element stress to zero (erosion). The strain at fracture, ε^F, is given by:

$$\varepsilon^F = [D_1 + D_2 \exp(D_3 \frac{P}{\sigma_{eff}})](1 + D_4 \ln\dot{\varepsilon})(1 + D_5 T_H) \quad (4)$$

where P is mean stress (pressure) and σ_{eff} is effective stress. Fracture/failure occurs when D reaches the value 1:

$$D = \sum \frac{\Delta\varepsilon_{eff}^p}{\varepsilon^F} \quad (5)$$

Finally, the Johnson-Cook model implementation in LS-DYNA also includes a spall criterion. The tensile pressure was limited to pressure cutoff (P_C = 350 MPa) in this case. The properties of aluminum 6061-T6, used for the simulation were taken from [17] and are summarized in table 2.

Table 2: The properties of 6061-T6 aluminum, according to [17].

Johnson-Cook strength model:

A [MPa]	B [MPa]	N [-]	C [-]	M [-]	$\dot{\varepsilon}_0$ [s^{-1}]
324.1	113.8	0.42	0.002	1.34	1.0

d [$kg \cdot m^{-3}$]	G [GPa]	T_m [°C]	T_r [°C]	C_p [$GPa \cdot °C^{-1}$]
2703	27.6	600	25	869

Johnson-Cook failure model:

D_1 [-]	D_2 [-]	D_3 [-]	D_4 [-]	D_5 [-]
-0.77	1.45	-0.47	0.0	1.6

Linear polynomial equation of state ($C_0 = C_5 = C_6 = E_0 = 0$):

C_1 [GPa]	C_2 [GPa]	C_3 [GPa]	C_4 [-]
74.2	60.5	36.5	1.96

5 Comparison of experimental and simulated velocity profiles

The sequential deformation of the flyer at four discrete times can be seen in figure 2. The false colors correspond to the actual velocities of the flyer. The velocity gradually increases. The elements on the sides of the flyer are deleted after exceeding the damage criterion (eq. 5).

The comparison of experimental velocity profile (solid black curve) with the result of the simulation (dashed red curve) is shown in figure 3. Both experimental and simulated records were taken in the top central part of the aluminum disc.

The expected stepwise character of both curves is typical for the acceleration of solid material by explosive. The steps are produced by a reflection of a shockwave in a flyer. The simulated velocities on the individual steps are close to the experimental ones as are the duration of the steps. The terminal velocity agrees very well, which is a sign of a correct overall energetic balance.

6 Conclusion

The acceleration of Al flyer with A-IX-1 was succesfully simulated using the LS-DYNA code. The properties of the explosive (detonation velocity and pressure, JWL parameters for the expansion isentrope) were completely calculated by Explo5 program, the properties of aluminum were taken from the literature. The simulated velocity profile shows a good agreement with the experimental one, measured with PDV. Both curves agree in shape, velocity values at the individual steps, their duration and the terminal velocities.

Acknowledgement

This work was supported by Grant Agency of Czech Republic grant number GACR 13-30441S.

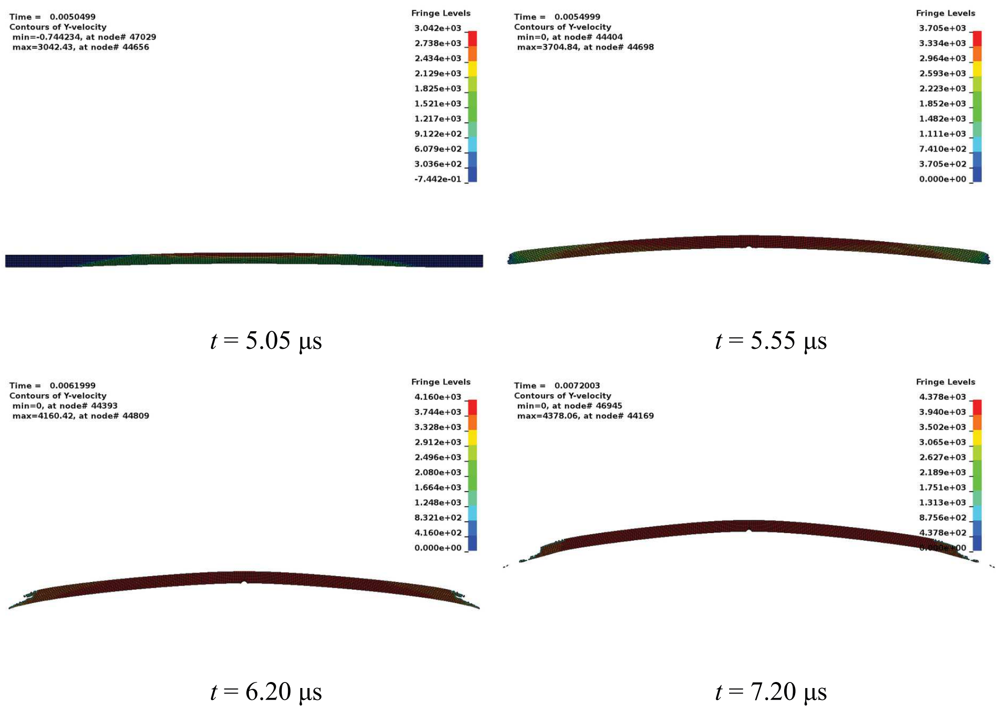

Figure 2: Subsequent deformation of the flyer. The velocity is included in figure as a fringe level.

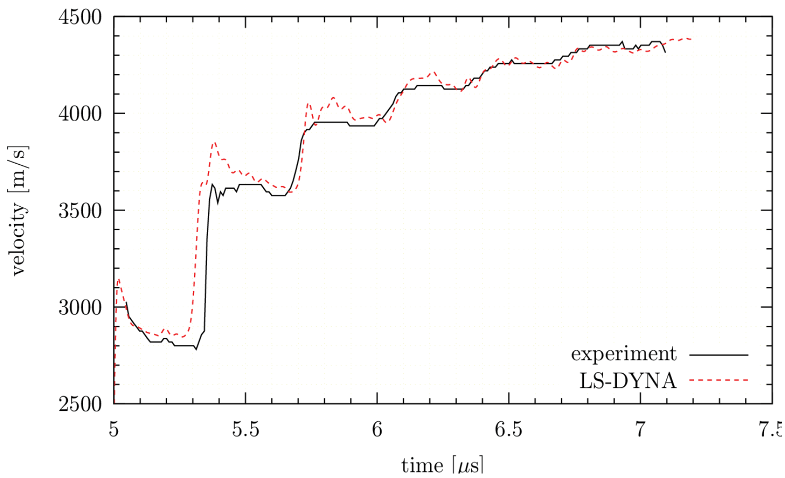

Figure 3: The comparison of experimental and simulated velocity profiles for nominally 1 mm Al disc.

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