Three-dimensional numerical simulation of the instability of the interface between two high-speed colliding metal plates

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Abstract. The dynamic processes which take place during high-speed impact of two metal plates with different densities are investigated using three-dimensional numerical simulations. It is shown that as a result of the impact the Rayleigh–Taylor instability forms which leads to the formation of three-dimensional ring-shaped structures on the surface of the metal with smaller density. The comparative analysis of the metals interface deformation process with the use of different equations of state is performed.

1. Introduction
The problem of explosive hardening and explosive welding is the actual issue for production of high-strength bimetallic compounds and constructions with the desired characteristics [1]. Explosive welding is a process of metallic compound production as a result of high-speed impact due to the energy of condensed explosives detonation products. The process is followed by the complex dynamic effects which are the subject of a number of experimental and numerical studies, see [2] for example. In [2] on the example of high-speed impact of lead plate with the plates of different metals the features of the processes in the near interface regions of the colliding plates are investigated experimentally.

The scheme of the experiment [2] is the following. The lead plate is thrown by the products of condensed explosive detonation to the steel plate under some angle with the speed several hundred meters per second. The plates become deformed with the formation of solid compound in some cases. The partial melting of the colliding surfaces takes place and the transition of the metals to the elastoplastic state occurs due the high energy release. So during some time (about 10 \(\mu s\) seconds) after an impact the metals are in the elastoplastic state and behave as pseudo-fluids before the backward transition starts. Circumstantial proof of that fact is the existence of crateriform splashes on the surface of steel plate in the direction of lead plate. The explanation of the splashes was given in [2] on the assumption of the Rayleigh–Taylor instability development. Such type on instability can be realized in the rarefaction wave which moves through the plates interface from the lead plate free side if the initial disintegration of discontinuity occurred with the formation of two shock waves. Acceleration in the rarefaction wave is directed to side of the metal with the smaller density which is the necessary condition of
the Rayleigh–Taylor instability development (the velocity and density gradients have different signs).

It should be noted that there are a lot of difficulties in experimental observations of the process in consideration due to the extremely high temperatures and pressures and very short times. In such conditions numerical modeling provides the possibility to obtain very precise effects that couldn’t be get in natural experiments. The paper is devoted to the numerical simulation of high-speed impact of two metal plates in the statement qualitatively similar to [2] using three-dimensional (3D) Euler equations and different equations of state.

2. Statement of the problem
Consider the interaction of the lead plate with the density $\rho \approx 11300 \text{ kg/m}^3$ and thickness $h = 0.002 \text{ m}$ with the steel plate ($\rho \approx 7900 \text{ kg/m}^3$) or the copper plate ($\rho \approx 8900 \text{ kg/m}^3$) of the same thickness. The lead plate is thrown in the vertical direction with the speed $w = 500 \text{ m/s}$. As the initial disturbance we set the point disturbance $500 \text{ m/s}$ of the velocity on the throwing plate surface. The initial pressure is equal to $P = 10^{12} \text{ Pa}$, acceleration is equal to $g = 10^7 \text{ m/s}^2$ and directed to the metal with the smaller density. The computational area is the cube with the edge length 0.004 m. We set slip conditions on the upper (upper surface of the throwing plate) and lower (lower surface of the target plate) boundaries and periodic conditions of the side faces.

Note that due to the large computational costs we don’t consider the whole development of the process during plates impact which is described above. Instead our statement qualitatively corresponds to the moment when the rarefaction wave from the free surface of the throwing plate reaches the interface. Calculations are carried out up to the moment when the disturbances from the initial impact reach the upper and lower boundaries of the computational area.

3. Mathematical model and numerical algorithm
Mathematical model is based on three-dimensional non-stationary two-component Euler equations [3] supplemented by equations of state (EOS). We use three different EOS namely: (i) ideal gas, (ii) barotropic gas and (iii) wide-range EOS for real metals.

As the first approach to explain the experimental results the model of ideal gas with the specific heat ratio $\gamma = 5/3$ was considered.

The second approach is the use the barotropic EOS with the sonic compression:

$$P = P_0 + E(\rho/\rho_0 - 1),$$

where $P_0$ corresponds to the curve of “cold” compression of the substance which coincides with the “cold” isentropic line, $E$— coefficient of the sonic compression equal to the module of elasticity in the solid phase.

As the third model we chose the wide-range semi-empirical EOS [4]. The EOS not only well describes the condensed phase of the substance under the low temperatures but also takes into account the phase transition from the solid to the liquid one. Wide-range semi-empirical EOS are based on the extensive experimental data concerning shock compression of the solid and porous substances under normal conditions. At the extremely high pressures and temperatures they have the asymptotics of Tomas–Fermi and Debye–Huckel.

Numerical algorithm is based on the physical processes and spatial directions splitting techniques. The set of equations is written in the characteristics form. We solve three one-dimensional systems along each coordinate directions independently using Roe numerical flux function. Time integration is performed using explicit Euler scheme. Spatial approximation order of the scheme is increased up to second with the use of hybrid schemes approach. In this approach the switching between the central and upwind differences is realized for each
Figure 1. The density isosurface and a cross section: the splash to the direction of lead plate; calculation with the use of ideal gas EOS.

Figure 2. The density isosurface and a cross section: the splash to the direction of lead plate; calculation with the use of barotropic EOS.

characteristics based on the sign of characteristics. The detailed description of the numerical algorithm could be found elsewhere [5].

The typical size of the computational grid is $100 \times 100 \times 100$. For the numerical simulations of the problems which are described by the hyperbolic system of equations the authors developed computer code TurboProblemSolver (TPS) [6]. TPS has modular structure and consists from the independent blocks responsible for different parts of the numerical method. TPS provides to the user the possibility to change numerical scheme, initial and boundary conditions and mass forces. The code is written in C++ and is parallelized using Message Passing Interface (MPI) package using domain decomposition approach.
4. Results of numerical experiments
The presented results concern the ideal gas EOS and barotropic EOS for the case of steel target plate.

For the ideal gas EOS with the point disturbance in the center of one of the plates we obtained the splash in the direction to the lead plate. The shape of the splash is similar to that observed in [2]. Figure 1 shows density isosurface at the time moment 5 µs after the impact. The domain $z > 0$ corresponds to the lead plate and $z < 0$ to the steel plate.

For the barotropic EOS we also get the splash in the direction to the lead plate. The splash has the crateriform shape. Figure 2 shows density isosurface at the time moment 5 µs after the impact. The results obtained using two different EOS are in qualitative agreement.

5. Conclusions
To conclude let us figure out the main features of the process obtained in the natural experiment and confirmed by our numerical study.

(i) The instability development on the interface of the metal plates is characterized by splashes from the metal plate with the smaller density to the plate with the greater density.

(ii) The increase of the throwing plate thickness with the fixed velocity leads to the disturbance wavelength growth on the interface.

(iii) The comparison of the results for the steel and copper target plate shows that for the copper plate the splashes have the smaller wavelength and grater amplitude.

References
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