Optimal shape of the striker for jetless hypervelocity impact

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Abstract. A hypervelocity impact with a rigid wall of an axisymmetric striker generating converging to the axis of symmetry shock wave (SW) is considered. An efficient method is proposed for calculation of the optimum shape of the striker and the corresponding optimal jetless flux, so that during all the interaction time the velocity of SW and velocity of movement of the beginning of contact of the striker with the rigid wall are equal. This realizes the so-called strong solution for the shock wave. In the example shown, the shape of the projectile is closed to conical, but unlike a cone the angle between the normal to the surface and the axis of symmetry decreases when moving from the periphery to the center.

1. Introduction

The obtaining of high pressures and temperatures for highly compressed substance, in other words, the obtaining extreme matter is one of the key problems for a broad range of scientific and practical tasks.

For example, the extreme compression of matter is essential to obtain various structures of chemical elements and compounds at high pressures and temperatures, as well as creating the conditions for nuclear reactions, including nuclear fusion reactions. The use of the cumulation phenomenon [1] for high energy densities, which are of great interest in physics, is widely known. When focusing of shock waves in cylindrical and spherical geometry, the energy supply is carried out indirectly through the creation of high pressure on the surface of a spherical or cylindrical body. In the case of high-speed impact, using shape close to conical, allows to put the energy directly in the vicinity of the shock front.

Ideologically, this work is closest to [2–10] in which a substance filling the conical target is compressed by plane striker. So in [6], it is shown the possibility of synthesizing diamond in conical targets, and in theoretical and experimental studies [2, 3]—nuclear fusion. In [7] the analysis of jetless shock compression of a plate on a wedged-shaped target is presented. In that work the problem is discussed in terms of the rotation of the flow behind oblique shock. It is noted that there is a strong solution with a high pressure behind the SW front and weak solutions with a lower pressure behind the front of SW. In the problem considered in [7] for the aluminum striker and a lead target are realized only solutions of week family for a lead target.

Unlike previous works in this paper the shape of the striker is not plate and is not set initially. The shape of the striker is determined from the calculation. In terms of the rotation of the flow behind oblique SW in this case we have solution of strong family in the vicinity of contact point.
2. Problem formulation
Considered scheme of the process of the cumulation of energy when high-velocity impact on a rigid wall is shown in figure 1, that may also be interpreted as a counter-collision of identical projectiles with cavities. Initially, the entire energy of the system is in the kinetic energy of the projectile, incident on a rigid wall with speed $U_0$. Consider the local interaction of the projectile with a rigid wall in the vicinity of beginning of contact, called contact point (CP). Behind CP the kinetic energy of the projectile is transferred to the energy of the reflected SW. If the speed of movement of the CP to the axis of symmetry is too high ($\alpha$ too small) then the pressure of reflected SW is low and nearly to the pressure for reflected SW for case of plane straightforward interaction. If the speed of movement of the CP to the axis of symmetry is too low then the SW overtakes CP and goes on the free surface and its pressure fall due to the rarefaction wave coming from the free surface.

Under optimal interaction here we mean the case when during the whole time of convergence of the reflected SW to the axis of symmetry the velocity of its front at CP exactly equal to the movement velocity of the CP itself. The shape of the striker and parameters of compression are called optimal in this case respectively. In this case we have maximum pressure behind reflected SW.

3. Strategy of the calculation
As stated above, the concept of optimal flow leads to a very simple formulation for numerical solution, using explicit shock tracking method on moving grids. In this case, the numerical region figure 1 is limited by moving boundary with the front of SW conditions and rigid wall boundary conditions at the top and at the right. Before the SW front the unperturbed substance moves at a constant set velocity $U_0$. The numerical region limited thus continually increases in size as the proliferation of SW. The code automatically increases the number of cells of the numerical grid to maintain a given spatial resolution. We start the calculations from the grid with only one cell. When the SW reach the axis of symmetry the boundary conditions are changed to the boundary conditions of rigid wall. Because the initial distance from each point on the surface
Figure 2. Contours of density (a) for an intermediate time; (b) just after that SW reaches the axis of symmetry.

of the cavity to the plane of symmetry is the linear function of time

\[ X = U_0 \tau, \]  

the shape of the cavity is easily restored from the calculation. Thus, one simple calculation immediately gives the solution for the optimal geometries and calculated itself optimal geometry.

4. Mathematical model and numerical method
The motion of the medium is described by the equations of Euler hydrodynamics for compressible inviscid media, or equations of elastic-plastic motion model of ideal plasticity as described by
Figure 3. The dependence of the maximum pressure and density in tungsten at impact velocity of 6.5 km/s for the initial radius of the cavity 1 cm, see: (a) full-time; (b) time 30 ns fragment in the region of maximum compression. The dotted line corresponds to the pressure, solid line is density.

Mises. The equations of motion of the medium are closed by equations of state SESAME [11]. The numerical method uses the basis of Godunov’s method for a curved quadrangular movable numerical meshes with explicit discontinuities tracking (contact discontinuities, shock waves). Unlike the original, the method includes new developments in the field of construction and optimization of numerical grids [12].

5. An example of the calculation
The calculation was performed for impact of tungsten projectile with a speed of \( U_0 = 6.5 \) km/s with a rigid wall; for cavity with an initial radius of start contact \( R_0 = 1 \) cm, in the axisymmetric formulation. The calculation is started from one cell. At the end of the calculation the number of cells increases to \( 64 \times 1024 \) cells. Figure 2 shows contours of density field for the two sequential points in time, illustrating the dynamics of the process. Figure 2(a) corresponds to the time when SW reaches the middle of the cavity. Figure 2(b) corresponds to the time when SW reaches the axis of symmetry. The dependence of maximum pressure and correspondent density on time is shown of figure 3.

The peak is achieved in the moment of reflection of SW from the axis of symmetry when the pressure exceeds 500 Mbar, with cell size of 2.5 \( \mu m \). The calculated dependence of CP coordinate on time gives information on the shape of the cavity. Since the cavity depth on time is determined by equation (1) one may exclude time and receive the shape of the cavity as dependence of the relative radius \( R/R_0 \) on the relative depth \( h/R_0 \), what is given on figure 4(a).

One can also easily determine the optimal inclination angle depending on radius. Figure 4(a) shows that the estimated optimal shape close to the cone, but is not a cone with a perfectly straight forming a cone. It is better visible on figure 4(b) where the dependence of the inclination angle on radius is presented. The angle of inclination to the surface of the cone decreases with decreasing radius first decreases abruptly, then gradually decreases in the middle part, and again sharply decreases at the end. This behavior is due to the increase in front velocity in the vicinity of CP in the process of interaction. This behavior reflects both physical and numerical features of the solution obtained.

For the plane case for cavity wedge-shaped self-similar solution (WSS) exists. We start the calculation with only one cell and the initial numerical solution is too rough and we have
inclination angle higher than the angle for WSS. The first abrupt decrease is mainly numerical effect explained by fast growth of number of cells in numerical region. For exact solution we would have initial inclination angle a lesser angle for WSS, and then the accelerated decrease of the angle of inclination due to increasing the cumulative effect with decreasing radius.

Calculations taking into account elastic-plastic behavior of the material showed that the effect of the elastic precursor is insignificant and the shape of the cavity should be determined according to the bulk wave.

6. Conclusions
It is shown that for a high speed counter-collision, there is unique special solution, referred to herein as optimal when the shape of the cavity in the impacting bodies is such that at a given impact velocity, the SW during the whole time of impact, until the exit on symmetry axis, reaches the free surface of the colliding bodies, but do not cross the free surface. In other words, we always have one point in cross section of the free surface reached by SW but we never have a free surface behind SW. Thus, the shape of the cavity computed uniquely and is fixed for a given material and impact velocity. In the planar case of collision there is a fixed optimum angle of impingement plates. An efficient method of calculating optimal parameters of the cumulative impact on the basis of numerical simulation in moving grids with tracking of contact discontinuities and shock waves is presented.

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References
[1] Zababakhin E I 1965 Phys. Usp. 8 295–8
[2] Bogolyubskii S L, Gerasimov B P, Liksonov V I, Mikhailov A P, Popov Yu P, Rudakov L I, Samarskii A A and Smirnov V P 1976 JETP Lett. 24 206–9
[3] Anisimov S I et al 1980 JETP Lett. 31 61–3
[4] Bushman A V et al 1988 Pisma Zh. Tekh. Fiz. 14 1765–9
[5] Ternovoi V Ya 1984 J. Appl. Mech. Tech. Phys. 25 715–20
[6] Lomonosov I V, Fortov V E, Frolova A A, Khishchenko K V, Charakhchyan A A and Shurshalov L V 2003 Tech. Phys. 48 727–35
[7] Charakhch’yan A A 2001 J. Appl. Mech. Tech. Phys. 42 14–20
[8] Charakhch’yan A A, Khishchenko K V, Fortov V E, Frolova A A, Milyavskiy V V and Shurshalov L V 2011 Shock Waves 21 35–42
[9] Khishchenko K V, Charakhch’yan A A, Fortov V E, Frolova A A, Milyavskiy V V and Shurshalov L V 2011 J. Appl. Phys. 110 053501
[10] Krasyuk I K, Pashinin P P, Semenov A Yu, Khishchenko K V and Fortov V E 2016 Laser Phys. 26 094001
[11] Lyon S P and Johnson J D 1992 SESAME: the LANL Equation of state database Report LA-UR-92-3407 (Los Alamos, New Mexico 8754: Los Alamos National Laboratory)
[12] Fortov V E, Goel B, Munz C D, Ni A L, Shutov A V and Vorobiev O Yu 1996 Nucl. Sci. Eng. 123 169–89