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NUMERICAL STUDY ON HYPERVELOCITY ACCELERATION OF FLYER PLATES BY OVERDRIVEN DETONATION OF HIGH EXPLOSIVE

ZHI-YUE LIU*, SHIRO KUBOTA**, and SHIGERU ITOH***

*Graduate School of Science & Technology, Kumamoto University, Kurokami 2-39-1, Kumamoto City, Kumamoto 860-8555, Japan ; **Department of Earth Resources Engineering, Kyushu University, Hakozaki 6-10-1, Higashi-ku, Fukuoka City, Fukuoka 812-8581, Japan ; ***Shock Wave and Condensed Matter Research Center, Kumamoto University, Kurokami 2-39-1, Kumamoto City, Kumamoto 860-8555, Japan

Abstract—In most applications of explosives to flyer acceleration, the detonation of explosives is usually regarded as a steadily progressing wave phenomenon in which the pressure of the detonation products immediately behind the wave front is characterized by the so-called Chapman-Jouguet (C-J) pressure value. This type of detonation is therefore routinely referred to as the C-J detonation behavior and the detonation products start to expand from this C-J state to accelerate the flyer plate to a high velocity status. Overdriven detonation, however, is a detonation process that can provide a higher or much higher pressure than does the C-J detonation. Taking use of the detonation products from the overdriven detonation to push the plate may lead the plate to reach a hypervelocity status not achievable by means of the usual explosive acceleration techniques. This paper presents a numerical study on two acceleration systems for hypervelocity acceleration of plates by the application of overdriven detonation of explosives. The first acceleration system is the so-called planar acceleration system, which some researchers also call as the multi-stage launcher system. The other acceleration system is the improved technique that is named as the converging tunnel acceleration system. The numerical method used for the study mainly follows the formulation of HEMP computer code. Through numerical study, it is found that both systems can give an obvious improvement on the ability to hypervelocity acceleration of plates. Moreover, the comparison of two acceleration systems shows that the converging tunnel system has more superiority over the planar acceleration system for hypervelocity acceleration of plates.

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Keywords: high explosive, hypervelocity acceleration, numerical study, overdriven detonation.

NOMENCLATURE

$A, B, C, R_1, R_2, \omega$	JWL parameters
C, S	constants in shock Hugoniot
E_0	detonation heat of explosive
P, V, E	pressure, specific volume or relative volume, specific internal energy
P_{CJ}, V_{CJ}, D_{CJ}	pressure, volume and detonation velocity at Chapman-Jouguet state
P_g	pressure in detonation products
V_0, ρ_0	initial specific volume, initial density
W	mass fraction of solid explosive, unreacted $W=1$, fully reacted $W=0$
U_s, U_p	shock velocity, particle velocity
Y_0, μ, Γ	yield strength, shear modulus, Gruneisen parameter

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INTRODUCTION

High explosives play an important role in the fields of shaped charges and high-speed accelerations. The use of explosives for acceleration can remove the limitation on the dimensions of the accelerated bodies that must be strictly satisfied in other acceleration techniques such as the light-gas gun equipment. In most applications the detonation of explosives usually progresses in its characteristic form that can be well explained by Chapman-Jouguet (C-J) detonation theory [1, p.14]. Following the Chapman-Jouguet viewpoint, the detonation pressure of the fully reacted explosive holds a maximum value that is called the C-J pressure and the detonation products start to expand from this C-J state to do work for the surrounding matter. Overdriven detonation, however, is a detonation process that can provide a higher or much higher pressure than does the C-J detonation. Taking use of the detonation products from the overdriven detonation to push the plate may lead to reach a hypervelocity status not achievable by means of the usual explosive acceleration techniques. In cylindrical or spherical geometry, the overdriven detonation can be self-developed as the initiation begins from the outer surface simultaneously, but in planar geometry, the formation of overdriven detonation must rely on an initial high input pressure sustaining with a period of time or an impact by a high-velocity object [1, p.41]. Recently, studies have actively been carried out on the application of the overdriven detonation to hypervelocity acceleration for spacecraft protection. A multi-stage launch system using explosives as the driving source has been investigated by several researchers, e.g., Gaille [2], Bat'kov [3] *et al.* and Sun *et al.* [4], for the attempt to gaining the hypervelocity debris in the laboratory environment. The system used by respective workers has the resembling planar geometrical arrangement. In this paper, beside that the planar acceleration system will be studied, we shall introduce a new acceleration system for the hypervelocity plate acceleration, which we call as the converging tunnel acceleration system. Numerical studies on both acceleration systems are performed and some features on the hypervelocity plate acceleration from the two acceleration systems are given.

NUMERICAL METHODOLOGY

The used numerical method mainly follows the formulation of the HEMP computer code [5]. The equations of continuity, motion and energy in 2-dimensional cylindrical or planar coordinate system are solved by Lagrangian finite difference scheme. The materials considered in this method may be explosives, compressible fluids, elastic-plastic media, and their combinations. The sliding boundary concept is introduced for the treatment of the interfaces that are formed by materials with great difference on the distortion capability.

All explosives are treated as the reactive fluids even for solid explosives. The detonation process of explosives is described by a simple 'C-J volume burn' technique [6] to represent the conversion of explosives from the initial condensed states to the final detonation products. This burn technique assumes that the mass fraction of the unreacted explosive is linearly proportional to the volume of the cell in calculation, and when the volume of the cell of the original explosive becomes equal to the volume of the detonation products at Chapman-Jouguet (C-J) state, the explosive is thought to be fully decomposed into the gaseous products. The expression of this model is given as follows:

$$W = \frac{V - V_{CJ}}{V_0 - V_{CJ}}, \quad V_0 \leq V \leq V_{CJ}$$

$$P = (1 - W)P_g \quad (1)$$

Before the start of the detonation, $W=1$, and at the finishing point of full reaction, $W=0$. The pressure P_g is calculated from the equation of state of detonation products of explosive.

For modeling the overdriven detonation of explosives, the Lee-Tarver ignition and growth model [7] or Johnson-Tang-Forest model [8] seem to be more optimistic methods even though these models were established primarily for handling problems associated with shock initiation under low or mediate pressure regime. However, such models involve a lot of physical parameters that have to be determined from large quantities of experiments. Except for several extensively studied explosives whose parameters needed in the models have become known, to most explosives those parameters are still unavailable. From the above reason, here, we still employ the 'C-J volume burn' model as an approximation to resolve the overdriven detonation zone. The procedures for this treatment are specified in the following. As the volume of the computational cell is equal to or less than the volume of detonation products at C-J state, the pressure of the cell is determined by the relation given in the above 'C-J volume burn' model. While, as the volume of cell is greater than the volume of detonation products at C-J state, the pressure is directly calculated from the equation of state of the detonation products using the volume and energy of the cell at that time. This treatment on the overdriven detonation means that the overdriven detonation zone is divided into a C-J volume burn area with the ensuing adiabatic compression regime.

The equations of state for the detonation products of explosives take use of Jones-Wilkins-Lee (JWL) equation of state form [9]. This equation has the following expression:

$$P = A \left(1 - \frac{\omega}{R_1 V} \right) \exp(-R_1 V) + B \left(1 - \frac{\omega}{R_2 V} \right) \exp(-R_2 V) + \frac{\omega(E + E_0)}{V} \quad (2)$$

For many explosives their JWL parameters have been determined from standard experiment called cylinder expansion tests.

The metals in the calculation are modeled to be elastic-perfectly-plastic materials with the von Mises yield criterion for the distinction of elastic and plastic deformation regimes. The hydrodynamic component (hydrostatic pressure) of the stresses is calculated from Mie-Gruneisen form of the equation of state using the Hugoniot, which is established from the experimental relation of shock velocity and particle velocity, $U_s = C + S U_p$, as standard reference [10]. The expression of Mie-Gruneisen equation of state is then given as:

$$P = \frac{C^2 (V_0 - V)}{[V_0 - S(V_0 - V)]^2} \left(1 - \frac{\Gamma}{2} + \frac{\Gamma V}{2V_0} \right) + \frac{\Gamma E}{V_0} \quad (3)$$

The deviators of stresses in the elastic-plastic materials are solved by the general Hooke's law. In the plastic region, the deviators are commonly adjusted by a factor so that the von Mises yield criterion equality can be satisfied.

SIMULATIONS OF TWO ACCELERATION SYSTEMS

Planar Acceleration System

Fig. 1 shows the schematic arrangement of this acceleration system. After the detonation of the first explosive charge the gaseous products push the metal impactor that contacts with the charge to a high-velocity status. This high-velocity impactor then impacts on the second explosive charge thereby inducing an impact initiation to the second charge. The explosion of the second charge accelerates the flyer plate. Here, in order to ensure the detonation incurred in the second charge is overdriven detonation, the impact velocity of impactor should be kept over a critical value below which only the common C-J detonation takes place. Considering that the impactor has more or

Table 1. JWL EOS parameters of PBX and SEP explosives

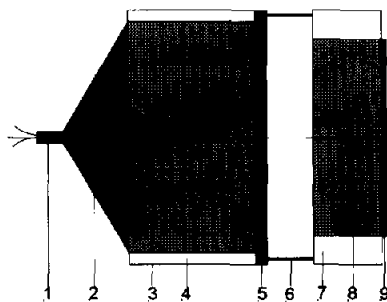
Explosives	$A(\text{GPa})$	$B(\text{GPa})$	$C(\text{GPa})$	R_1	R_2	ω	$E_0(\text{GPa m}^3/\text{m}^3)$
PBX	1129.3	23.718	1.476	5.691	1.491	0.295	6.945
SEP	365.0	2.310	0.093	4.3	1.00	0.28	2.830

Table 2. Chapman-Jouguet properties of PBX and SEP explosives

Explosives	$\rho_0(\text{kg/m}^3)$	$P_{CJ}(\text{GPa})$	$D_{CJ}(\text{km/s})$
PBX	1680	25.24	7.84
SEP	1310	15.9	6.97

less different deformations on the impact surface due to the influence of the side rarefaction from detonation products and plate itself, the second charge is arranged to have a smaller diameter than the first charge in order to acquire an impact as flat as possible. At meantime, since the overdriven detonation is an unsteady process and is easily affected by the rarefaction coming from the backward detonation products to be converted into the common C-J detonation, the second explosive charge should also be arranged with a shorter length to overcome such influence.

To this system, we plan to carry out the numerical simulation by two separate steps, for it is difficult for us so far to accomplish the whole calculation at one time. First of all, we calculate the flying speed of the impactor under the loading of the first explosive charge. Secondly, we calculate the acceleration process of the flyer plate from the action of the second explosive charge that is assumed to be impacted by an undeformed impactor with a reasonably prescribed velocity. The first calculation provides us the information on the selection of the prescribed velocity value. The explosive used for the first charge is a plastic-bonded explosive (PBX) containing 85% wt. HMX high explosive and 15 % wt. other addition. The second charge is an SEP explosive (PETN 65 wt. % and paraffin+resin 35 wt. %). Two explosives were manufactured and provided by Asahi Chemical Co. (Ltd.), Japan. The JWL parameters for detonation products equation of state of those explosives [11] are listed in Table 1 and the C-J detonation property values [11] are given in Table 2. Copper is used for impactor and flyer plate. The material constants of copper (together with steel material used in the following section) [12] pertinent to the calculation are given in Table 3. In the calculation, the dimensions of first charge, impactor, second charge and flyer plate are $\Phi 40 \times 40$ mm, $\Phi 40 \times 2$ mm, $\Phi 30 \times 15$ mm, $\Phi 30 \times 0.5$ mm, respectively. Except for the interfaces between metals and explosives, all boundaries are assumed as free boundary. Fig. 2 exhibits the configuration of impactor and detonation products during the impactor acceleration



1- Detonator, 2- Plane wave generator, 3- Explosive I, 4- Explosive holder I, 5- Impactor, 6- Spacer, 7- Explosive holder II, 8- Explosive II, 9- Flyer plate

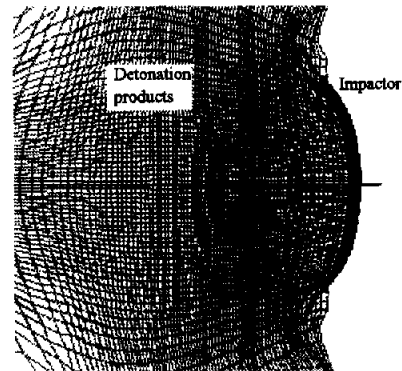


Fig. 2. The configuration of the impactor accelerated by the detonation products.

Fig. 1. The illustrative diagram of planar acceleration system.

Table 3. Material constants for the constitutive equations of copper and steel

Materials	$\rho_0(\text{kg/m}^3)$	$C(\text{km/s})$	S	Γ	$Y_0(\text{GPa})$	$\mu(\text{GPa})$
Copper	8930	3.95	1.49	2.0	0.45	46.6
Steel	7916	4.58	1.51	2.02	0.78	98.7

by the expansion of detonation products of the first charge. The detonation of the first charge is accomplished in a common C-J detonation way. It can be found that with the increase of time the accelerated impactor undergoes the different deforming histories at the radial positions. The margins of the impactor have slower velocities and also are subject to the severely in-uniform deformation owing to the side rarefaction from both the detonation products and plate itself. The velocity of the impactor at the rear free surface near the axis is depicted in Fig. 3 as a function of the flying distance. It predicts the maximum possible velocity of the impactor obtained by the acceleration of the first explosive charge under given conditions.

On the calculation of the flyer plate acceleration, we make the following replacement for achieving that purpose. The impactor is assumed to move at a prescribed velocity determined on the basis of the above calculation and also to keep an undeformed shape before its impact onto the second charge. Meanwhile, the diameters of the impactor, second charge, and flyer plate are assumed to be equal. At the beginning, let us look into the critical velocity value required for the

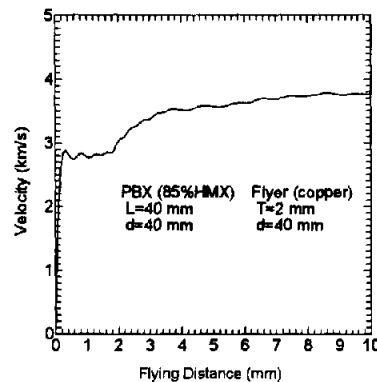


Fig. 3. The velocity increase of the impactor with the increasing flying distance from the explosive acceleration. Explosive: PBX, 40mm in diameter and 40mm long; Impactor: copper disc, 40mm in diameter and 2mm thick.

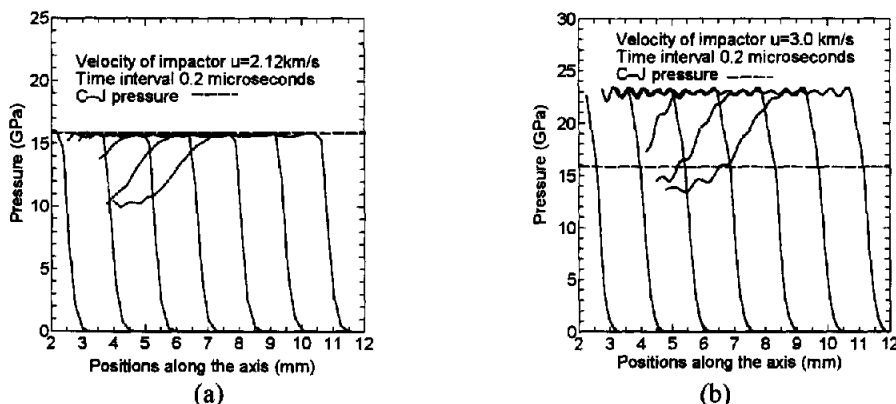


Fig. 4 The detonation pressure distributions along the axis of the charge after the impactor striking on the second charge at velocities of 2.12 km/s (a) and 3.0 km/s (b).

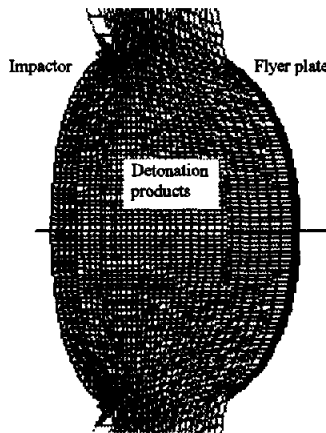


Fig. 5. The computational mesh diagram in the acceleration of flyer plate by overdriven detonation from the impact of the impactor. Impactor, copper, $\Phi 30 \times 2$ mm, initial velocity 3.0 km/s; Explosive, SEP, $\Phi 30 \times 15$ mm; Flyer plate, copper, $\Phi 30 \times 0.5$ mm.

impactor to cause an overdriven detonation in the charge. The founding may be obtained by several trials with the change of the velocity of the impactor. As the velocity of the impactor is equal to 2.12 km/s, the detonation in the second charge can be regarded as the C-J detonation. The calculated detonation pressure profiles along the axis at several time instants are shown in Fig. 4. It demonstrates that the peaks in the calculated pressure profiles approximately fall into the neighborhood of 15.9 GPa, which is the C-J pressure of SEP explosive. When the impactor reaches a velocity of 3.0 km/s, the calculated peak detonation pressures in the charge, as shown in Fig. 5, are far greater than the value of C-J pressure. This shows that the charge exploded under overdriven detonation condition. Fig. 6 gives the computational mesh configuration at the time of 3 μ s after the impactor striking the charge at velocity of 3.0 km/s. Because of the lateral expansion of detonation products the flyer is unevenly deformed and the central portion of the flyer has much faster speed than the margins. Fig. 7 shows the velocities of the flyer plate originating from the acceleration of the charge in variation with the flying distance when the impactor was prescribed with velocities of 3.0 km/s and 2.12 km/s respectively. As demonstrated before, under 2.12 km/s condition, the flyer plate was only accelerated by normal C-J detonation

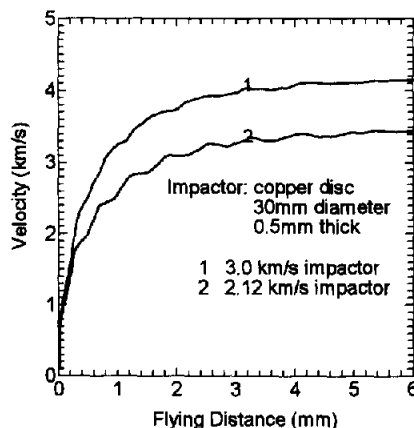


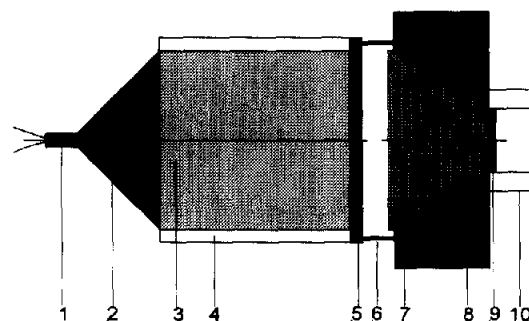
Fig.6. The calculated velocity variation with the flying distance for the flyer plate as the second charge is subject to impact of impactor at velocities 3.0 km/s (curve 1) and 2.12 km/s (curve 2), respectively.

of the charge. The discrepancy on the velocity amplitudes indicates the improvement of the acceleration ability by overdriven detonation.

Converging Acceleration System

From the computational results of the planar acceleration system, it can be seen that the effect of the side rarefaction is considerably severe on the acceleration of the plate. In order to eliminate this influence over the plate acceleration and also to increase the acceleration ability, we devised the following converging acceleration system to obtain the improvement. In place of the straight circular second explosive charge in the planar acceleration system, here, a conical explosive charge contained in a steel cylinder is employed. The flyer plate is mounted at the end of the conical charge with a small sectional area, while, the other end with a larger sectional area faces the impactor. The schematic diagram of this system is illustrated in Fig. 7. As long as the conical angle is set to be with a reasonable range, the arrangement is not only able to eliminate the influence of the side rarefaction but also able to produce the effectiveness of Mach reflection of detonation wave [13,14] along the conical tunnel surface in the steel cylinder. The generation of Mach detonation can further increase the local pressures near the surface of the tunnel. If the diameter of the small section of the charge is not so large, this effect will spread to strengthen the whole detonation wave in propagation. The converging conical angle, α , can be chosen between 20–40 degrees because for most explosives Mach reflection of detonation wave would take place at an incidence angle over 50 degrees [13]. Such determination of the converging angle ensures that the incidence angle of the detonation wave on the tunnel surface falls into the range of 50–70 degrees. In this system, the dimensions of the first charge and impactor are, respectively, 40mm diameter by 40 mm long and 40 mm diameter by 2 mm thick. The conical charge is of 30 mm diameter on the large sectional end and 10 mm diameter on the small end as well as of a length of 15 mm. The flyer plate is of 10 mm diameter by 0.5 mm thick. The steel cylinder has the outer diameter of 42 mm and the length of 15 mm with a tunnel portion being the same size of the conical charge. From the above given dimensions, the conical angle is hence estimated to be 33.5 degrees approximately. The explosives used for the first charge and the conical charge here are also PBX and SEP, respectively, similar to those used in the former planar acceleration system.

Similarly, the whole calculation is also accomplished by two sequential procedures; the determination of the velocity of the impactor and the acceleration of the flyer plate by explosion of the conical charge. The velocity of impactor originated from the loading of the first charge is completely equivalent to that obtained in the case of the planar acceleration system. On the acceleration of the flyer plate from the explosion of the conical charge, it is not possible for us to use the same treatment on the initiation of the second charge as done in the planar acceleration sy-



1- Detonator, 2- Plane wave generator, 3- Explosive I, 4- Explosive holder, 5- Impactor, 6- Spacer, 7- Explosive II, 8- Converging tunnel, 9- Flyer plate, 10- PVC tube

Fig. 7. The illustration of the converging tunnel acceleration system.

stem because of some computational difficulties. Instead, the impact of the impactor onto the second charge is simplified to be a constant velocity piston imposing on the surface of the second charge holding within a reasonable short period of time, say $0.4 \mu\text{s}$. This time interval was simply estimated as an approximate quantity by summation of two subsequent time periods; the first is the time needed for the shock wave traveling from the impact surface to the rear surface of the impactor after the impact and the other is the time taken by the rarefaction starting at the rear surface to arrive at the impacting surface of the impactor. Under those prescribed conditions, the calculation on the detonation of the conical charge and its acceleration to the flyer plate becomes possible. As indicated in the above section, the overdriven detonation only appears in the charge under the impact speed over 2.12 km/s . We therefore take two initial velocities of 2.5 km/s and 3.0 km/s into consideration. At the beginning of the calculation a piston boundary holding velocities given above, is assumed at the impact end of conical charge with larger area and lasted for 0.4 microsecond s. After that period the piston boundary is then converted into a free boundary. The calculated pressure contours for both situations are given in Fig. 8. The detonation starts from the left-hand side and moves to the right-hand side. The variation of the grayscales represents the pressure changes in the computational field and the bright portions correspond to shock wave or detonation wave front where the pressure has the maximum magnitude. Obviously, the local higher pressures on the conical surface are clearly visible. This high pressure region prevents the appearance of the side rarefaction and in consequence, only is the back rarefaction left to decrease the strength of the progressing overdriven detonation. It should be noted that in the maps of the pressure contours the grayscales ahead of the detonation wave or shock wave front are set only to distinguish the materials in the computational field, not standing for the pressure value in those regions. In the following, the pressure profiles on the axial positions are calculated for observation on the propagation of the overdriven detonation in the charge and the results are presented in Fig. 9. The time interval between two consecutive profiles is 0.2 microsecond s. It illustrates that no matter what situation is considered the peaks of the profiles are larger than the 15.9 GPa C-J detonation pressure of SEP. From these results, it is known that the detonation induced in the charge is indeed the overdriven detonation.

Finally, a computational image of the acceleration process of the flyer plate is presented in Fig. 10. The conical charge was initiated by the 3.0 km/s velocity at the impact end surface with 0.4 microsecond duration. Different with the case of the planar acceleration system, in this case the flyer relatively keeps a uniform shape on the radial plane, not forging violently. Fig. 11 exhibits the calculated velocity of the flyer varying with the flying distance under 3.0 km/s

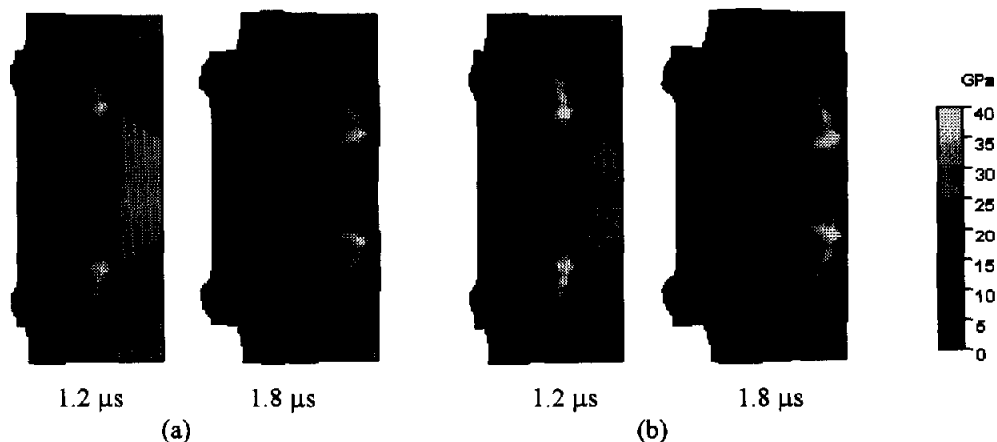


Fig. 8. The pressure contours of detonation products in the conical charge initiated by 2.5 km/s velocity piston (a) and 3.0 km/s velocity piston (b) with $0.4 \mu\text{s}$ duration on the large sectional end surface of conical charge.

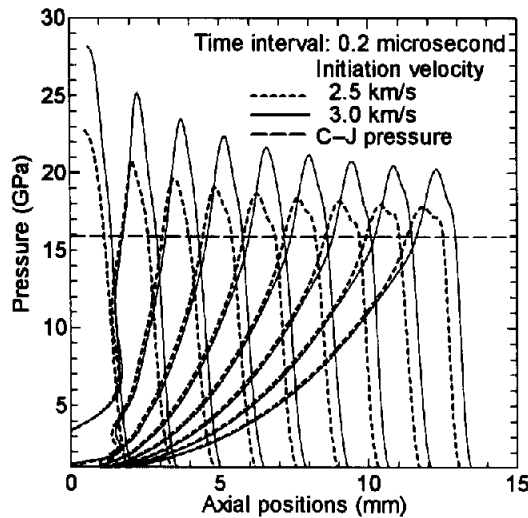


Fig. 9. The pressure profiles of detonation products of the conical charge along the axial positions at several time instants under two initiation velocity conditions; together also giving the C-J pressure for comparison.

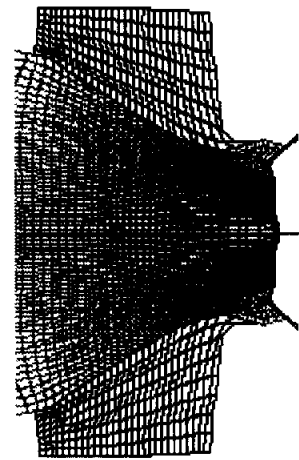


Fig. 10. The acceleration of flyer plate after the explosion of the conical charge.

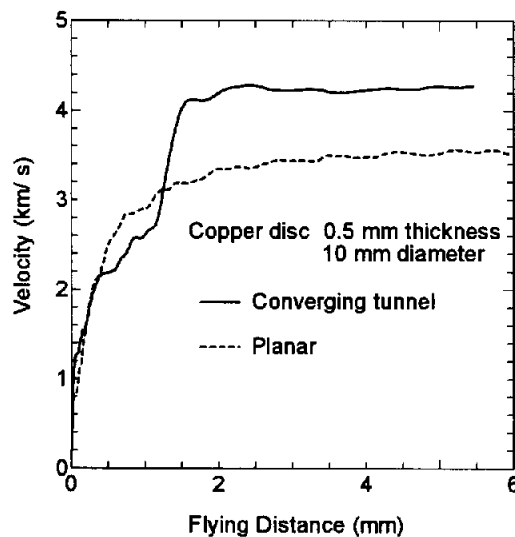


Fig. 11. The velocity of the flyer plate from the acceleration of the conical charge initiated at 3.0 km/s constant velocity with 0.4 μ s duration. Together also giving the velocity of flyer plate from the planar acceleration system under the same conditions for comparison.

initiation velocity on the conical charge. The velocity obtained refers to the velocity value of the central part of flyer on the back free surface. It shows that the velocity quickly rises to the maximum value in a short flying distance. Together with this velocity plot, the velocity of the flyer in planar acceleration system under the same given conditions (i.e., not including the impactor in the computation) is also calculated for comparison. It is shown that the velocity of the flyer produced from the converging tunnel system is greatly larger than that achieved in the planar acceleration system.

CONCLUSIONS

Two acceleration systems taking use of the overdriven detonation of high explosive for achieving the hypervelocity flyer have been studied numerically. The calculations demonstrate that the utilization of the overdriven detonation of high explosive is a promising technique to gain a hypervelocity status associating with researches on impact dynamics. Comparing the two acceleration systems on the flyer velocity and the flyer shape during acceleration stage, it may be found that the converging tunnel acceleration system is of some superior features over the planar acceleration system. In the future work, the experimental studies should be set up for verifying the effectiveness of these acceleration systems. In addition, the effects of explosives, types of flyer material, and flyer dimensions to the hypervelocity acceleration should be further explored.

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