Explosive Laboratory Devices for Dynamic Shock Loading of Materials in Mbar Pressure Region

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Abstract. Dynamic methods utilizing strong shock waves are used for investigating the properties of condensed matter at very high pressures and temperatures. Explosive driven plate impact tests have been conducted to find out the shock Hugoniot of materials up to pressure of 2 Mbar. Explosive cascading utilizing overdriven detonation waves in high explosives produced by flyer impact from the first stage to accelerate comparatively thin flyer plates to very high velocities have been demonstrated. Numerical simulations using Autodyn 2D/3D have been performed to optimize the various parameters in two stage explosive assemblies to accelerate flyer to velocities exceeding 10 km/s. Shock pressure up to 20 Mbar has been successfully measured using explosive assemblies in a convergent flow. Expertise and infrastructure available in TBRL for launching metal flyers to high velocity and monitoring its in-flight velocity and profile have been discussed in this paper.

1. Introduction
The study of material behaviour under extreme conditions of pressure and temperature is a fascinating subject for scientific community all around the globe for years and this quest is still not over. This helps to reveal the truth of natural occurrences from core of earth to the Sun and other planetary bodies. Although static methods using Diamond Anvil Cells and other such devices are employed to generate the high pressure in the materials, but the range of achievable conditions by these method is limited. In order to generate high temperature in DAC external heating devices such as lasers or conventional heaters are required, however, in shock compression the generation of temperature is part of the process itself. For experiments at pressures higher than those obtainable by the static methods, resort has to be taken to the inertial forces set up in the material itself by the acceleration accompanying strong shock waves.

The dynamic methods utilizing strong shock waves are used for investigating the properties of condensed matter at very high pressures and temperatures and are of particular interest to scientists and technologists working in the various disciplines of science and engineering. The shock waves which propagate in the materials at supersonic velocities, typically at several km/s, subject the material to high pressure from few hundred kbar to Mbar pressure region. The contact explosive detonation [1] produces triangular pressure pulse in target materials in the range of 200-500 Kbar, which is limited by the availability of high power explosives and shock impedance of materials. Shock waves can be generated in number of ways and the most common is the impact onto a target specimen by the projectiles accelerated by a variety of systems such as gas guns, electromagnetic rail guns, plasma guns, laser and explosives etc. The impact of explosively accelerated flyer on
target produce uniaxial strain states and is widely used for the determination of shock hugoniot of the materials and equation of state [2, 3] of different materials at high pressure. The terminal velocity of flyer is a function of explosive to metal mass ratio and the Gurney energy of the explosive and a flyer can be launched to a maximum velocity of approx 5 km/s. An impact of a steel plate moving at 5 km/s with the stationary steel plate generates a shock pressure of the order of 1.5 Mbar.

To generate still high pressures in materials, we have used explosive cascading technique [5], which allows to utilize overdriven detonation waves in high explosives produced by impact from the first stage flyer (driver plate) to accelerate comparatively thin flyer plates (driven plate) to very high velocities. The thicknesses of driver and driven plates, flight distances, thickness of the second stage explosive and the separation of the two plates from the explosives to maintain planarity are the few issues which need to be addressed for designing a cascaded plate impact experiment. Numerical simulation is the best tool to optimize the different dimensions of a cascaded explosive system. We have demonstrated two stage explosive system to launch the metal flyer to 7-8 km/s in planer configuration and up to 15 km/s in a spherically convergent system [6]. Shock pressure up to 20 Mbar has successfully been measured experimentally across a converging shock wave. Dynamic methods of investigating the properties of condensed matter at high pressure and temperature are based on the kinematics parameters of the shock waves. For experimental determination of different shock parameters the experimental techniques such as electrical shock arrival pins, fibre optical pins and streak photography have been used in the present studies.

2. Conventional Plate Impact Experiments

In this type of experimental setup a flat metal plate is launched to different velocities using the explosives, gas gun etc. On impact at target, this generates pressures much higher than those achievable by contact explosive detonation. The control over the dimensions of the flyer and careful design of target restricts the strain state in target to 1-D, which simplifies the use of theoretical models and mathematical calculations for determining the shock hugoniot of the materials. Even the pressure pulse in the target is approximately rectangular in shape, thus allowing broader area for deployment of sensors to monitor the shock propagation. We have established explosive driven plate impact technique to launch the 3-5 mm thick metal flyers of diameter 120 mm to velocities from 1-5 km/s. The explosive-metal assemblies were finalized after inputs from theoretical models, which predict the terminal flyer velocity to a reasonable degree of accuracy. These assemblies were used to in the laboratory to determine the shock hugoniot of the metals, ceramics, polymers and heavy metal alloys.

2.1 Theoretical Models for Terminal Flyer Velocity

The use of an explosive charge detonation to drive the metal fragments was first studied by RW Gurney [7, 8] in early 1940’s. The theoretical model relied on the partition of an explosive energy between the KE of metal and the explosive gases driving it. This model yielded a simple relationship between the final metal velocity, the explosive energy, and the ratio of the mass of driven metal to that of loaded explosive. For a metal launched by unconfined explosive charge, the final flyer plate velocity is given as

\[
V_p = \sqrt{2E} \left[ \frac{1 + \left( \frac{M}{C} \right)^3}{6 + \frac{M}{C}} \right]^{1/2}
\]

where \(\sqrt{2E}\) is Gurney velocity coefficient, which is specific to a particular explosive and is determined experimentally for each explosive.

Aziz et al [9] considered the metal flyer as a rigid piston driven by expanding detonation gases and predicted the final plate velocity as
These two models ignored the effect of the side rarefaction losses and shock characteristics of the materials, which affect the energy coupling due to decrease in impulse and different shock impedances of materials and hence the plate velocities. These models predict the same terminal flyer velocity for different explosive-metal combinations with same charge to metal mass (c/m) ratio.

Backofen and Weickert \cite{10} incorporated the forward momentum of detonation products and modified the Gurney relation as

$$V_p = \sqrt{\left(V_p\right)^2 + \left(u_p\right)^2}$$

where $V_p$ is the plate velocity given by Gurney relation and $u_p$ the initial particle velocity imparted to metal surface. The particle velocity has been found to be dependent on nature and thickness of explosive metal combination through a relation

$$u_p = \frac{\rho_p D}{1 + \frac{M}{C}} \cdot \frac{1}{3 \cdot \left(1 + \frac{9}{16} \left[\frac{\rho_e C_0}{\rho_p D}\right]\right)}$$

where $\rho_p, \rho_e$ are densities of metal plate and explosive respectively, $D$, the detonation velocity and $c_0$ is the sound velocity in the plate material.

These models do not account for the deformity of the flyer plate during motion, caused due to the side rarefactions so the experimentally measured velocities are different from those predicted by Gurney, Aziz or Backofen. Further flyer plate assembly design with introduction of air gap between the flyer and explosive were analysed and introduced by HS Yadav \cite{11}, which are presently used in our studies.

2.2 Design of Explosive-Metal Assemblies and Determination of Shock Hugoniot

The above discussed models were used to determine the dimensions of explosive assembly to achieve a particular flyer velocity. Plane wave initiated octol explosive was used to accelerate flyer plates of diameter 120 mm and thickness 3-5 mm to velocities from 1-5 km/s. Further refinement in the preliminary explosive assembly design was done through modelling and simulation using AUTODYN. Experiments were conducted to validate the results of simulation and to determine the velocity and planarity of the flyer prior to impact. Experimental techniques deploying optical, electrical and photographic methods have been established to record the flyer plate velocity and profile and post impact shock velocity in the target material.

The figure 1(a) below illustrates the use of optical pins to record the flyer plate velocity and profile. The explosive was initiated through a plane wave lens consisting of fast and slow octol and baratol explosives respectively, which accelerates the flyer to its terminal velocity. This flyer impacts the optical pins, producing a light flash, which has been recorded by the streak camera in fig 1(b). The pins at different height w.r.t target record velocity, whereas pins at the same height are used to calculate the impact symmetry. The flyer velocity and profile prior to impact was also recorded using electrical shock arrival pins and is shown in figure 1(c).

![Fig.1](https://example.com/fp00001.png)

**Fig.1.** (a) Explosive assembly with optical and electrical pins to record velocity and planarity of flyer (b) Streak camera record and (c) oscilloscope record showing arrival of flyer prior to impact
These assemblies were used to determine the shock hugoniot of metallic, Ceramics, Rock Samples etc. The figure 2(a) shows the experimental assembly using the symmetric impact technique used to determine the shock hugoniot of materials wherein electrical and optical shock arrival pins were used to record the shock velocity in the target materials. The thickness of the explosive was changed along with the air spacing in between explosive and flyer to achieve flyer velocities from 1.2 to around 5 km/s. Shock Hugoniot between pressure and particle velocity found for the metal sample has been shown in fig 2(b).

3. Cascaded Plate Impact Experiment

There is an upper limit to the velocity of flyer, which can be achieved by single stage explosive device as the velocity depends principally on the Gurney Energy of explosive (a constant) and explosive to metal mass ratio. The velocity increases with charge to metal mass ratio and reaches an asymptotic value. So there is an upper limit on velocity and hence the pressure which can be generated in the target. But quest to realize the higher pressure states goes on. The technique of using explosive and impedance cascading or staging is popular among the shock physics community. We have established the concept of cascaded explosive system to launch metal flyers to velocities of the order of 7-8 km/s and even more.

In staged flyer launch systems, impedance cascading and explosive cascading techniques can be used to accelerate the flyer to very high velocity. In the impedance cascading, buffer plates of different materials and varying thicknesses are deployed, in order of decreasing shock impedances as target to first stage. A striker plate is explosively accelerated to terminal velocity, which then hits a set of buffer plates. In this manner the driven plate can be launched to a velocity equal to the free surface velocity of the last buffer plate. The concept of achieving high flyer velocity by this method was given by Balchan and Cowan [12] and was demonstrated by the authors in their previously published studies [13].

3.1 Explosive Cascading

In the explosive cascading arrangement, the first stage explosive launches a metal flyer to its terminal velocity. At the terminal end it impacts another explosive and produces overdriven detonation in it. The overdriven detonation in the second charge decays rapidly, so it is essential to use optimum thickness of it to drive the second stage flyer. This flyer is relatively very thin, but gets accelerated to very high velocities.

In an two stage explosive system, if the velocity $u_0$ of first flyer is more than the CJ particle velocity of explosive, overdriven detonation travels in the second stage explosive and the strong detonation speed $D$ can be deduced as

$$D = \frac{D_2^2 + (\gamma + 1)^2 u_0^2}{2(\gamma + 1)u_0}$$
where \( D \) is overdriven detonation velocity, \( D_j \) is normal detonation velocity and \( \gamma \) is the isentropic expansion co-efficient of detonation products. The final velocity of the second stage flyer can be estimated by relations given by Wen Shanggang et al [4]. In the present studies explosive cascading technique has been utilized to launch the metal flyer to extremely high flyer velocities.

### 3.2 Simulation and Experimental Validation

In a cascaded system the velocity and thickness of the driver and driven plate, second stage explosive thickness and flight distances need to be optimized to get maximum efficiency. The numerical simulation using AUTODYN 2D was performed to finalize the various parameters. A two stage explosive assembly with Octol explosive is shown in the figure 3 (a). The experimental assembly used to propel a metal flyer, launched a nearly flat flyer which made an impact on the second stage explosive, in turn accelerating the second flyer to high velocity. The results predicted through the AUTODYN simulation are shown in the figure 3(b).

![Figure 3(a). Two Stage Experimental Setup 3(b) Simulation Result of](image)

The experimental assemblies were evaluated to monitor the second stage flyer velocity and planarity. The ionisation and optical pins were deployed along with the high streak photography to monitor the motion of second stage flyer.

This method has successfully been demonstrated by us to generate pressures or the order of 3Mbar in the different target materials. Beyond this pressure we can use the three stage arrangement, but there are practical limitations which introduce mis-alignment problems, limiting the use of this method. Even the thickness of explosive and flyers decreases in each stage, which are very difficult to fabricate with adequate strength, flatness and within acceptable tolerances. Still higher pressures have been achieved by translating the planer arrangement to spherical one, thus introducing the concept of convergence to realize pressures in excess of 10 Mbar.

### 4 Converging Detonation and Shock Waves for Mega bar Pressure Generation

In order to realize the conditions of pressure and temperature inside the cores of planetary bodies and to simulate the conditions of impact of terrestrial bodies, converging detonation systems along with the two stage explosive cascading systems can be used. Either a cylindrical system converging on axis or a spherical system with peak pressures at centre is generally used. The phenomenon of convergence of a spherical detonation wave at the centre and the cylindrical wave on the axis was studied by LD Landau and KP Stanyukovich in 1944[14]. They found out that the pressure rise in convergence as \( r^{-1.13} \) in spherical cases and as \( r^{-0.47} \) in the cylindrical case. If the effect of converging detonation waves is augmented by a converging shock wave, tremendous rise in the pressures occurs. Practical use of the convergence of detonation waves and shock waves has been demonstrated by Al’tshuller et al [4] to achieve very high pressures in the target materials.
In this technique the explosives used are in hollow cylinders or spheres. The outer surface is initiated simultaneously to generate converging detonation waves in the explosives propagating towards the cylinder axis or sphere centre. The converging detonation is further used to accelerate the metal liners of matching shape. The theoretical relations to find the collapsing liner velocity have been given by R. Cheret [15] and Hirsh [16]. The liners can be accelerated to very high velocities generating pressures upto 5 Mbar in single stage arrangements. If the concept of explosive cascading discussed earlier is extended to the spherical geometry, pressures of the order of 10-20 Mbar or even more can be achieved.

In one such experimental assembly we used Octol explosive to accelerate the first stage 4 mm thick liner. This liner impacted the second stage 10 mm thick explosive, which was used to accelerate the second liner. The velocity of the second liner was estimated using simulation nearing 14 km/s at a radial location where target was placed. The results of AUTODYN simulation are presented in figure 4(a) showing the predicted value of the collapsing liner in the range 13.6-14 km/s at different locations. This liner impacted the hollow metal target in the form of concentric metal shells. Different types of optical, electrical and piezoelectric pins were deployed at the interfaces between target shells at possible azimuth locations to record the converging shock wave. Shock velocity of the order of 20-22 km/s was recorded with calculated pressures reaching nearly 20 Mbar. In the two experiments, the average pressures were measured at \( \frac{r}{r_0} \) of 0.024 and 0.029 from centre of convergence and are compared with the simulation results in figure 4(b).

**5 Comparison of Two Stage with Single Stage Explosive Cascaded Systems**

This flyer velocity can be increased considerably using two stage systems wherein higher pressure in excess of normal C-J detonation pressure is developed in the inner pad due to an over-driven detonation, and hence a higher velocity for the inner flyer plate. The numerical simulation shows the comparison of a single stage and two stage systems within same dimensions. Cascaded system allows to achieve detonation pressure of the order of 1 Mbar in second stage explosive whereas in the single stage system the convergent flow allows detonation pressure of 500 kbar or more with large duration. The predictions of the explosive impulse in the two systems are shown in figure 5(a). As the pressure pulse is very sharp in the two stage systems; the inner flyer plate has to be very thin. Thickness of this flyer must be much smaller than width of the pressure pulse. The velocity time history of the flyer in a single stage vs two stage explosive system is shown in fig 5(b).
6. Conclusions
A two stage explosive system both in the planer and converging geometry has been designed and successfully tested. Materials have been shock loaded to pressure upto 2.5 Mbar in planer assembly and upto 20 Mbar in converging system.

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Fig 5(a) Flyer velocity history in single and two stage systems (b) Impulse delivered to the liner in staged system