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Chapter 2

EXPLOSIVE TECHNIQUE FOR GENERATION OF HIGH DYNAMIC PRESSURE

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Summary. Dynamic loading methods developed at National Chemical Laboratory for Industry (NCLI) for materials processing by the use of explosives described and their features are discussed. The methods are classified into two groups; planar shock loading method and cylindrical convergent loading method. The former is suitable both for measurement of shock parameters and for interpretation of experimental results by a simple model, while the latter is useful technique for shock treatment of large amount of sample materials. Recovery devices of various kinds at NCLI are also presented.

1. Introduction

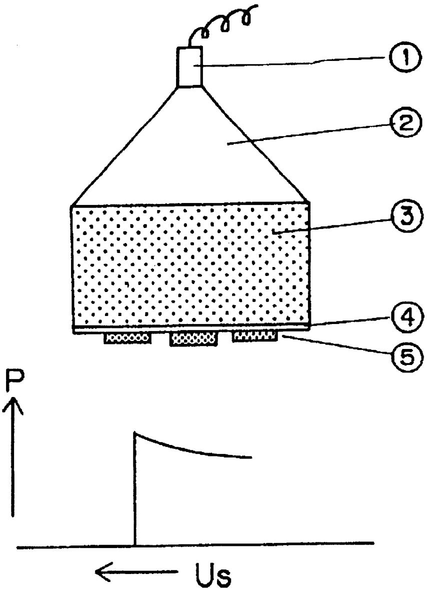
It is well known that, with the exception of nuclear material, chemical explosives are the most energetic substances. Explosives have an available energy of 4–8 kJ/kg and liberate *k* it in a time of 10^{-5}–10^{-6} seconds through a rapid chemical reaction, "detonation". Consequently, the power of detonation for a l-kg high explosive amounts to 10^{11}–10^{12} watts. This power is larger than the total power of all the electric power stations in Japan. Thus, the use of explosives gives us a cheap and easy means for generating high dynamic pressures in condensed materials.

In 1955, Walsh and Christian (Walsh *et al.*, 1955) reported the dynamic compressbilities of some metals in the pressure range 10–50 GPa, which were obtained by use of the high explosives. Since then, many kinds of explosive techniques have been developed and, at present, it is not difficult to generate strong shock waves with pressures of a few terapascals (Beaumont, 1977; Derentowicz *et al.*, 1979). Moreover, dynamic high-pressure technology using explosives has been applied to many industrial processes, such as metal working, the consolidation of powder particles, the activation of chemical substances, new material synthesis and so on. As far as the advanced utilization of explosives is concerned, it is of great importance to have the optimum design for explosion systems. Moreover, it is indispensable to establish fundamental techniques for so-called explosion control in terms of space and time; e.g., techniques for producing plane, cylindrical and conical detonation waves, techniques for causing the collision of two detonation waves, initiation of detonation with an accurate time delay, and simultaneous initiation at multiple points.

This section describes explosive methods for generating high dynamic pressures and recovering shock treated specimens, which are mostly used in our laboratory, the National Chemical Laboratory for Industory (NCLI).

2. Explosive Contact Method

The method shown in Fig. 1 is the most common, the "explosive contact method" or "explosive direct method". A plane detonation wave is initiated in



①Detonator, ②Explosive Lens, ③Main Charge, ④Attenuator, ⑤Specimen

Fig. 1. Shot assembly of explosive contact method and pressure profile of induced shock wave.

Table 1. Some parameters of explosive lens of NCLI.

Effective diameter	65, 100, and 150 mm
Flatness of plane wave	Less than 5×10^{-8} s
Container material	Polystyrene
Explosive	Nitromethane: low detonation velocity explosive Hydrazine nitrate solution with hydrazine hydrate: high detonation velocity explosive
Angle of cone	78°

the interface between the charge and the specimen material. On arriving at the
the interface between the charge and the specimen material. On arriving at the
interface, the detonation wave induces a plane shock wave in the specimen through a thin attenuator plate. Generally, a one-dimensional (plane) shock wave is required both for making precise experimental measurements of shock wave parameters and for simplifying the theoretical interpretation of shocked states. The explosive lens system at NCLI has specifications shown in Table 1. An original feature is that liquid explosives are used in our lens system.

Figure 2 shows the calculated pressure (P)-particle velocity (U_p) curves for the detonation products of some standard explosives which are used at NCLI. The Hugoniot P-U_p curves for some inert materials are also shown in Fig. 2. (Marsh, 1980). Both the P-U_p curves and detonation parameters for explosives are easily calculated by methods described in the references (Duball *et al.*, 1963), (Kamlet *et al.*, 1968).

Pressure and particle velocity at the interface between detonation products and specimen must be continuous (Walsh *et al.*, 1955), (Duball *et al.*, 1963), where the attenuator plate is neglected because of its small thickness. Thus the intersection of the explosive and inert curves in the P-U_p plane represents both reflected state in the detonation products and an induced state in the specimen. We can, therefore, determine the shock parameters induced in the specimen, if the Hugoniot curve is known.

When the Hugoniot of the specimen is unknown, we need to measure the shock velocity (U_s) of the specimen. On the basis of the shock impedance match method (Walsh *et al.*, 1957), the shock state is given by the intersection of the explosive P-U_p curve and the straight line starting from the origin point with a slope of: $\rho_0 \times U_s$ (ρ_0: the initial density of the specimen material).

In general, as seen in Fig. 2, the highest pressures obtained from the contact method range from 60 to 70 GPa. Pressures less than 10 GPa. are produced by using weak explosives and/or by the shock attenuation method (Seay *et al.*, 1961), (Stripe *et al.*, 1970), called the shock impedance mismatch method (see Fig. 3).

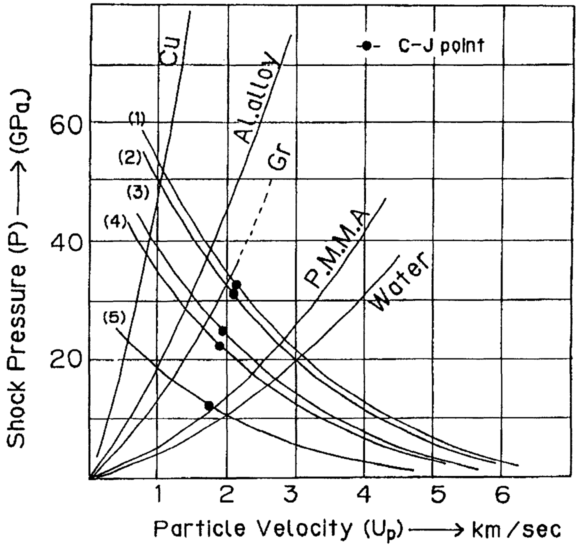
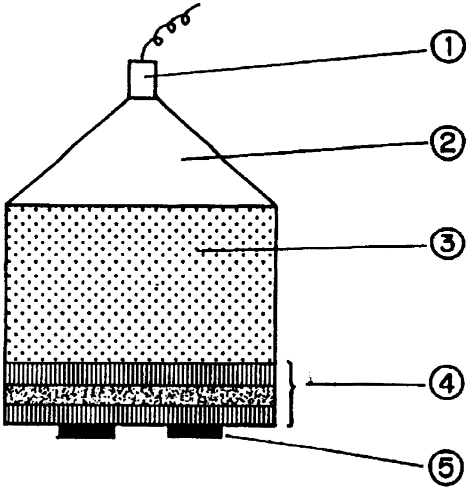


Fig. 2. Shock waves generated by explosive contact method. Inert materials are water, polymethyl methacrylate, graphite, aluminum alloy and copper.

(1) HMX/binder = 94/6, ρ_0 =1.74 g/cc, D=8.52 km/sec
(2) Octol, ρ_0 =1.80 g/cc, D=8.44 km/sec
(3) Comp.B, ρ_0 =1.66 g/cc, D=7.75 km/sec
(4) Cyclotol, ρ_0 =1.57 g/cc, D=7.48 km/sec
(5) Nitromethane, ρ_0 =1.13 g/cc, D=6.26 km/sec

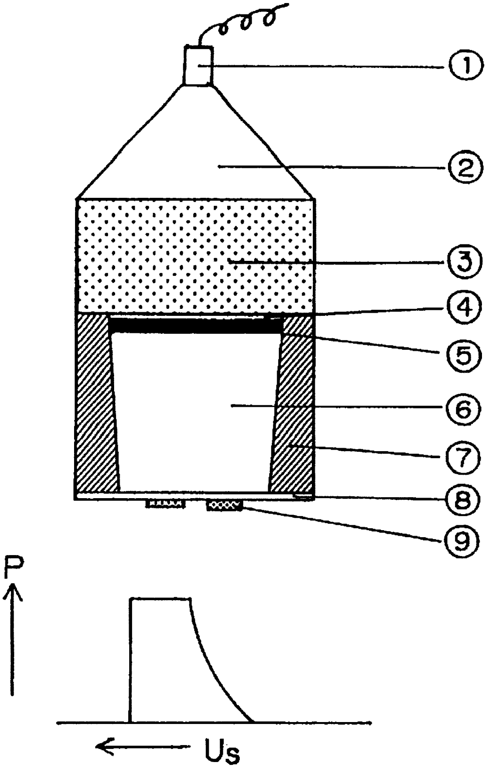


①Detonator, ②Explosive Lens, ③Main Charge, ④Attenuator plates (Copper/PMMA/Copper), ⑤Specimen

Fig. 3. Low pressure-plane wave compression assembly by impedence mismatch method.

3. Flyer Impact Method

When we need much higher pressures than those obtained by the contact method, the flyer impact method, as shown in Fig. 4, is used. In this method, a metal flyer plate, accelerated to a high velocity by a detonation wave, collides normally with a target plate. The impact of the flyer plate generates shock waves in both the flyer and target plate (specimen). In Fig. 5, curves F_1 and F_2 show the reflected Hugoniot curves of copper flyer plate with velocities (W) of 2 km/sec and 5 km/sec, respectively. The reflected curve is the mirror image of the normal copper curve and it must start from the state $P = 0$, $U_p = W$, in the P-U_p plane. The intersection of the flyer and the target curve gives the induced shock state, just as in the explosive contact method. Therefore, we can easily determine the shock state if only the Hugoniot relations for flyer and specimen and the flyer velocity are given.



①Detonator, ②Explosive Lens, ③Main Charge, ④Shock Attenuator, ⑤Flyer Plate, ⑥Air Gap, ⑦Metal Barrel, ⑧Screen Plate, ⑨Specimen

Fig. 4. Shot assembly of explosive driven flyer impact method and pressure profile of induced shock wave.

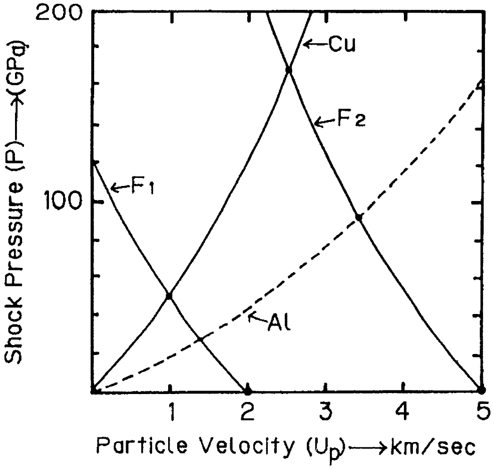


Fig. 5. Shock waves generated by flyer impact method. Hugoniot relations for Cu and Al are obtained from reference (Al'tshuler *et al*). F1 shows reflected curve for copper plate with velocity of 2 km/sec. F2; velocity of 5 km/sec.

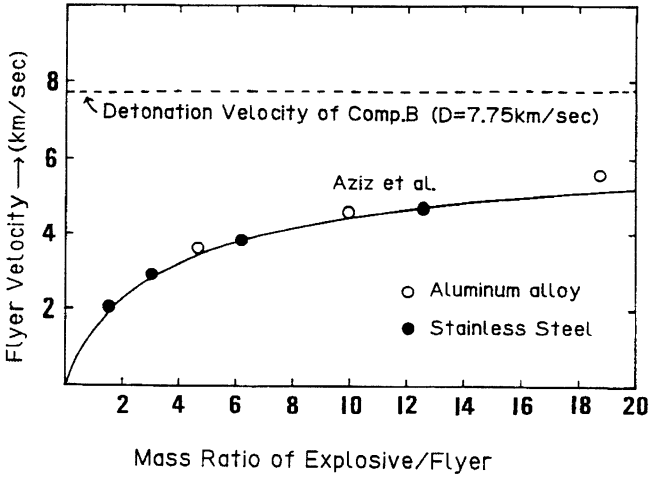


Fig. 6. Relationship between velocity of flyer and mass ratio of explosive/flyer.

The shock pressures produced by this method increase proportionally to the approximate value of $\rho_0 W^2$. Hence, the higher the density and velocity of the flyer, the higher the pressure that can be obtained. It is known that flyer velocity depends on the mass ratio of explosive and flyer. Figure 6 shows the experimental results between the speed of the flyer plate and the explosive/flyer mass ratio, which were obtained at NCLI. In the experiments, a metal plate (aluminum alloy or stainless steel) was accelerated by a planar slab of Comp.B explosive and the velocity was measured with electrical contact pins. The solid curve in Fig. 6, calculated by Aziz's method (Aziz, 1961), is in good agreement with our experimental results. Theoretically, it is possible to accelerate a flyer to the limit velocity, i.e., to detonation velocity. However, in practice it is rather difficult to obtain a heavy metal flyer with a velocity of more than 5–6 km/sec. Accordingly, the practical pressures obtained by this method are less than several hundreds GPa.

Some useful methods have been researched and developed in order to produce ultra high pressures in the *TPa*-range. They are, for example, the use of Mach detonation waves (Argous *et al.*, 1965), overdriven detonation waves (Al'tshuler, 1976), the conical imploding flyer impact method and others (Sheng *et al.*, 1981), (Ivanov *et al.*, 1982).

4. Cylindrical Compression Method

Cylindrical compression methods using explosives have been developed, mostly by Russian researchers, in order to investigate physico-chemical effects in condensed substances which are preserved after explosive shock treatment. Since the first report by Riabinin in 1955 (Riabinin, 1956), dynamic loading effects have been studied for a great many substances by the use of cylindrical methods (Graham *et al.*), (Nellis *et al.*, 1982). Figures 7-1, 7-2 and 7-3 illustrate the explosive-cylindrical methods which are used at NCLI. They are called, respectively, the cylindrical contact method, the cylindrical flyer impact method and the double explosive layer–cylindrical flyer impact method. In these methods, a detonation wave or flyer impact at first causes a converging conical shock wave in the cylindrical specimen surrounded by a metal container. Then, the head collision of the incident shock wave occurs at the cylinder axis (see Fig. 7). When the angle of the head collision is smaller than.a certain critical value, a regular reflection of the incident shock wave occurs and the specimen is double compressed by the reflected shock wave.

Zones (I), (II) and (III) in Fig. 7-1 denote the unshocked, single- and double-shocked states respectively. In the case of collision angle larger than the critical one, an irregular reflection occurs and a Mach wave with a nearly planar front is generated (see Fig. 8). The front of the Mach wave is called the "Mach stem" or "Mach disk". Under a steady condition of Mach stem formation, the propagation velocity becomes constant and equal to the detonation velocity.

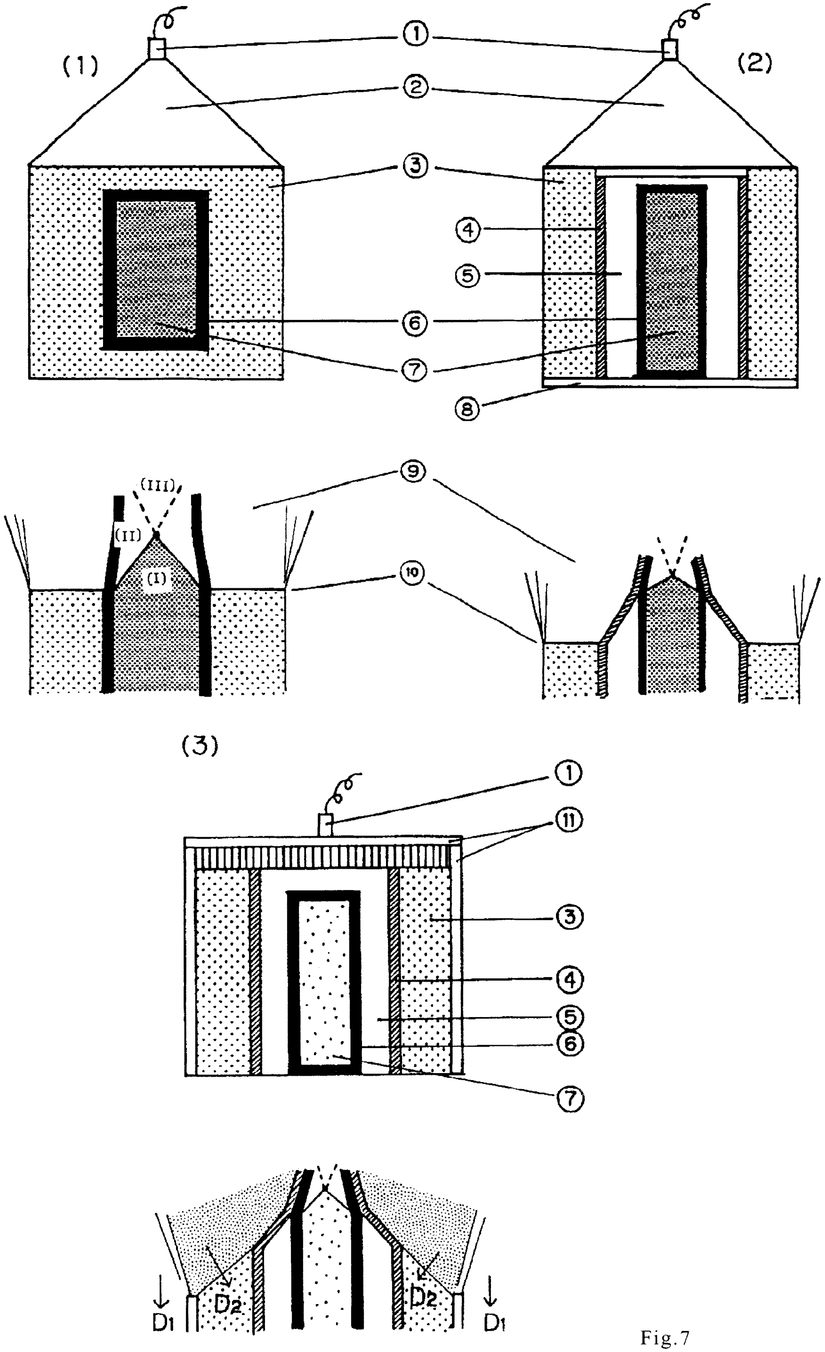


Fig.7

In Fig. 8, I, II, III and IV denote unshocked, single shocked, Mach shocked and double shocked states (regular reflections), respectively. Lines XM and YN express the slipline, which distinguishes the Mach state from the regular reflection state. On both sides of the slipline, the pressure is the same, but the particle velocity, the shock temperature and the entropy are different across the slipline. This is because the Mach state is a single compression state, whereas the reflected state is a double compression state.

Recently, Mach waves produced by cylindrical methods has been studied by many workers (Adadurov *et al.*, 1967), (Morris *et al.*, 1984), (Gogula *et al.*, 1981), (Voskovoinikov *et al.*, 1987), (Martynov *et al.*, 1986). The summary of their experimental results is as follows.

(1) The flow becomes steady after a Mach stem has travelled a distance equal to approximately twice the specimen diameter.

(2) The propagation velocity of a steady Mach wave is just equal to the detonation velocity of the explosive used.

(3) A Mach stem is planar or nearly planar. Moreover, the shape and the size are constant under steady conditions.

(4) The Mach region is a single compression state. Consequently, the Mach state is expressed by one-dimensional Hugoniot relations. This makes the calculation of shock parameters easy if the Hugoniot U_s-U_p relation for the specimen material is given.

(5) Although the diameter of a Mach stem depends on experimental conditions, it generally increases with the collision angle of the incident shock wave. In Table 2, the experimental results of Mach wave diameter by Voskovoinikov *et al.* (Martynov *et al.*, 1986) are listed.

Unlike the plane compression method, the cylindrical method is disadvantageous in terms of the homogenous compression of specimen material due to the complicated flow interaction. However, several methods have been developed for making homogenous compression. One is to place a small metal bar, called a "mandrel", at the axis of the cylinder, in order to try to prevent Mach wave formation (Babul *et al.*, 1975). Another useful method is to generate a steady Mach wave whose Mach stem diameter is equal or nearly equal to the specimen diameter. As described by Balchan et al. (Balchan *et al.*, 1972), the condition for enlarging the Mach stem diameter without decreasing the shock pressure is satisfied by applying cylindrical flyer impact methods.

Fig. 7. Explosive cylindrical compresion method. (1) Cylindrical contact method, (2) Cylindrical flyer impact method, (3) Double explosive layer-flyer impact method.

①Detonator ②Explosive Lens ③Main Charge Explosive ④Flyer ⑤Air Gap ⑥Specimen Container ⑦Specimen ⑧Base Plate ⑨Explosion Gas ⑩Detonation Front ①Sheet Explosive

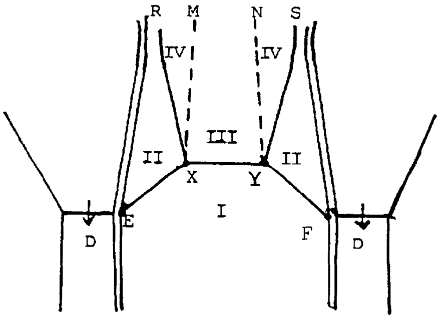


Fig. 8. Flow configuration of Mach wave generated by cylindrical compression method. EX and YF show incident shock front. XR and YS:reflected shock front, XY:Mach wave front, XM and YN:slip line, D:detonation front. (I): unshocked zone, (II): single shocked zone, (III): Mach zone, (IV): double compression zone.

Table 2. Experimental Mach stem diameter. (Voskovoinikov *et al.*)

	Specimen density	Porosity	Mach stem diameter
Magnesium	1.55 (g/cm3)	0.10	12.1 (mm)
"	0.80	0.53	10.5
Aluminum	2.71	0	9.8
"	1.22	0.55	7.6
Graphite	2.20	0	–
"	1.22	0.64	6.4
Iron	2.50	0.68	–

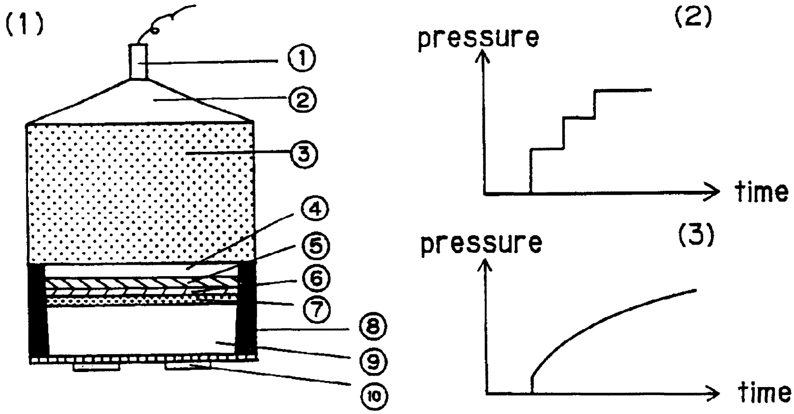
Mach wave is generated by the method shown in Fig. 7-1.

Explosive: RDX/TNT=50/50, ρ_0=1.68 g/cc, *D*=7.65 km/sec, 60 Φ x 60 mm specimen: 20 mm (diameter) x 60 mm (length).

5. Isentropic Compression Method

Shock compression is always associated with an increase in both temperature and entropy in a compressed specimen. This is undesirable in many cases; such as thermal decomposition under shock and/or residual high temperature, thermal relaxation of the mechanical effects produced by shock compression, etc. In these cases, dynamic isentropic compression methods are used, because the high pressure state produced by isentropic compression is similar to that produced by static compression (isothermal compression). In the USA and the USSR, an ideal method for isentropic compression of condensed substances has been developed (Hawke *et al.*, 1972), (Pavlovskii *et al.*, 1978), in which a strong magnetic field, produced by magnetic flux compression, is used to compress a specimen contained in a metal tube. This method is not practical, however, because the device is complicated and too expensive. Moreover, it is difficult to recover the specimen after compression.

The simple method shown in Fig. 9, which was originally developed by Russian researchers (Kompaneets *et al.*, 1972), (Adadurov *et al.*, 1981), is used in our laboratory. In this method, a composite flyer made of multi-layered plates, each of which has different shock impedance, is smoothly accelerated by explosion products. As shown in Fig. 9, the impact of the flyer generates a step wave or a ramp wave in a target specimen, where neither temperature nor entropy increases by much (Lyzenga *et al.*, 1981). Therefore, this method is called the "nearly isentropic compression method" or the "quasi-isentropic compression method".

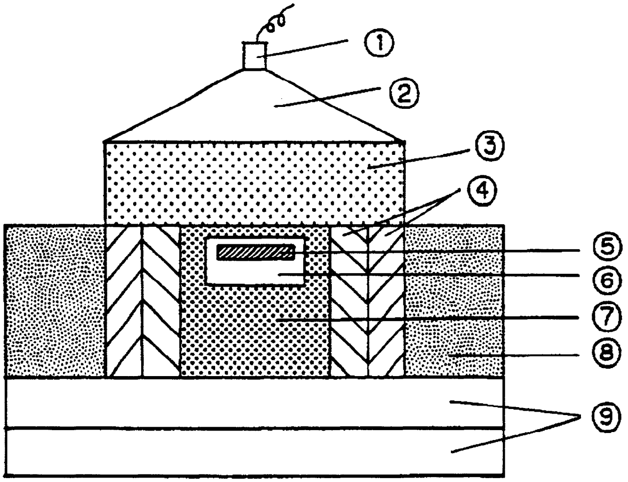


①Detonator, ②Explosive Lens, ③Main Charge, ④Air Gap, ⑤Copper ⑥Aluminum, ⑦PMMA, ⑧Metal Barrel, ⑨Air Gap, ⑩Specimen

Fig. 9. Quasi isentropic com.

6. Recovery Method

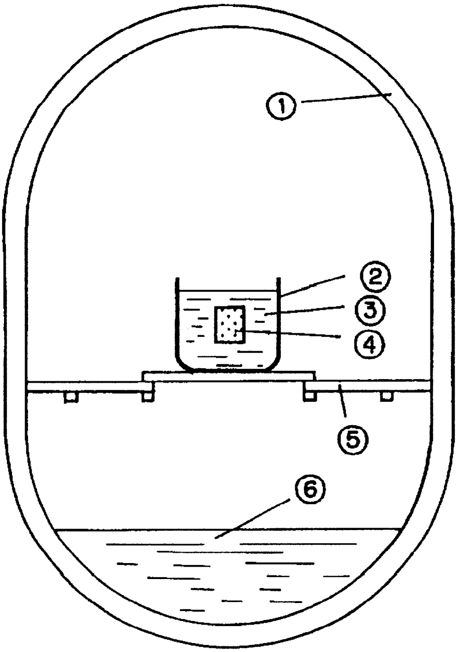
For the purpose of clarifying residual effects in a specimen material which has been subjected to a dynamic loading wave, it is indispensable to recover the specimen. Hence, various methods have been developed to accomplish this. Figure 10 illustrates one of our recovery devices for plane compression. In our devices, several kinds of metals are used for the container material, including molybdenum, copper, stainless steel, and aluminum alloy. The best one is chosen after consideration of the compression factors: the incident pressure, the difference of shock impedance between specimen and container, contamination of the specimen from the container, the possibility of generating gas-like species, etc. Usually, our specimen container is covered with a brass capsule, which makes it easy to remove the specimen by machine processing. As to the device shown in Fig. 10, where shock impedance of the container material is much higher than that of the specimen, we must note some special effects of shock interaction on compression. One is the effects of the reflected plane shock wave, which is generated at the interface between specimen and container and compresses the specimen to higher densities than those caused by the incident shock wave alone. Another is the effect of the radially converging shock wave, which starts from the lateral interface between specimen and container and travels toward the center of the specimen. The pressure of the converging shock wave increases with the decrease of its radius and the head collision produces a strong shock wave, which causes heterogeneous compression of the specimen (Davidson *et al.*).



①Detonator, ②Explosive Lens, ③Main Charge, ④Steel Tube, ⑤Specimen, ⑥Specimen Container, ⑦Brass Container, ⑧Lead Block, ⑨Steel Plate

Fig. 10. Recovery assembly for plane compression of specimen.

In the cylindrical compression method, we use a shot assembly as shown in Fig. 11, which makes recovery of the specimen reliable. This method not only makes it possible to increase the time duration of high pressure in the specimen, but also suppresses the flight of the specimen container at high speeds. The reason is that a large amount of water, surrounding the explosive charge, prevents rapid free expansion of the explosion products, which is effective for accelerating the flyer in the flyer impact mebhod. Moreover, this assembly is successful in decreasing residual heat effects, since the specimen container is rapidly cooled down by the bottom water in the explosion chamber.



①Chamber Wall: made of steel plate and reinforced concrete., ②Plastic Bucket, ③water, ④Explosive Compression Device, ⑤Steel Plates and Pipes for Supporting Shot Assembly, ⑥Water

Fig. 11. Recovery shot assembly in explosion chamber.

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