Optical Measurement Techniques under Shock Compression using Rotating Mirror Type Streak Camera

Optical Measurement Techniques under Shock Compression using Rotating Mirror Type Streak Camera*

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Synopsis

An optical measuring system by means of streak photography has been developed to obtain precise Hugoniot equation of state and optical absorption spectra of solids under shock compression using the two-stage light gus gun described in the preceding paper. The system utilizes light from a 1 kJ high intensity xenon flash lamp with about 10 torr Xe filling pressure. A continuous writing streak camera of rotating mirror type with a maximum writing rate of 13.5 mm/μs has been constructed to observe nonsynchronizable shock phenomena produced with the gun. The streak camera with a slit 23 μm in width (which corresponds to the slit image 92 μm in width on the film) is currently operated at the writing rate 10 mm/μs. Hugoniot equation of state is determined with an accuracy ±1 % using the inclined mirror technique. The release adiabat (i.e. adiabatic release path) from the shock compressed state is measured with the buffer technique. An optical absorption spectrographic system has a spectral response of 300-700 nm and wavelength dispersion of 8.3 nm/mm on the film.

I. Introduction

When shock wave research in our group was first performed by explosive method, optical observations with a rotating mirror streak camera developed by ourselves was used to examine the performance of plane wave generators and to determine the Hugoniot equation of state for various materials. Using both the argon flash gap and the inclined mirror techniques, shock compression experiments were performed for Fe_3O_4,[1,2] α-Fe_2O_3,[1,2] GaAs[2,3] and GaP.[2,3] Details of the experimental techniques have been reported in the previous report.[4,5]

Recently a two-stage light gas gun described in the preceding

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paper[6] has been constructed at RIISOM. Although the inner diameter of the gun is 20 mm and smaller than the diameters of the explosive plane wave generators, qualities of shock wave produced by the impact of projectile, such as flatness and smoothness of shockfront, are much better than those of the explosive plane wave generators. Attainable shock pressures produced by means of the two-stage light gas gun are also higher than those produced by the explosive method of moderate scale experiments. We have planned to carry out more precise Hugoniot measurements and optical absorption spectroscopy under shock compression using the two-stage light gas gun. However, the optical measuring systems used for the explosive method are not applicable for this case because of substantially non-synchronizable shock phenomena. A new optical measuring system applicable to the gun have been reconstructed and now in operation.

In this report the instrumentation for optical measurements with a newly developed rotating mirror streak camera is described in detail together with the measuring techniques for shock compression curve and optical absorption spectra under shock loading.

II. Instrumentation System

The instrumentation system has been designed and constructed for measurements of precise shock compression curve and optical absorption spectra under shock compression using the two-stage light gas gun. Figure 1 shows the schematic of the instrumentation system. Plane shock wave is produced by impact of a projectile bearing flyer plate against target plate at high velocities exceeding 4 km/sec. Impact velocity is one of the shock parameters and precisely measured with the magnetoflyer method.[7] The pulse signals induced in a pair of pickup coils by the passage of the magnet inside the projectile are recorded by a transient recorder (Biomation 8100) with a sampling time of 50 nsec. The projectile just before the impact is monitored with a 150 kV flash x-ray system of 30 nsec exposure. A xenon flash lamp developed in our laboratory is used for the light source to illuminate the target assembly. The light reflected from the target assembly is recorded with a continuous writing streak camera of rotating mirror type. The details of the target assembly for measurements of shock compression curve or optical absorption spectra will be described in the following sections.

1) Breakage-Wire Trigger-Pulse Generator

In order to trigger the transient recorder, flash x-ray and xenon lamp, the breakage of a 0.12 mm diameter copper wire placed to inter-

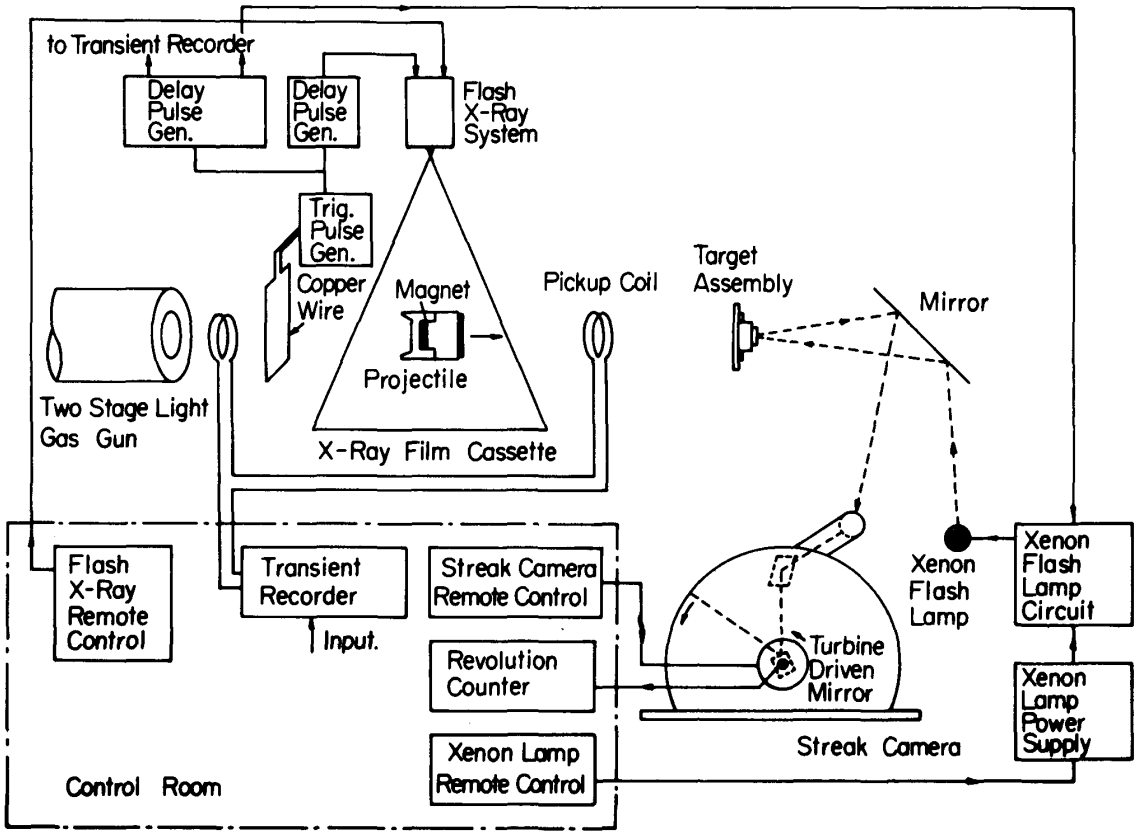


Fig. 1. Block diagram of instrumentation system for optical measurements by means of streak photography.

cept the outer edge of the projectile is used. The stretched copper wire is soldered at four terminals on the holding plate set near the first pickup coil between both the pickup coils for the magnetoflyer method (see Fig. 2). Figure 2 shows the circuit diagram of the trigger pulse generator for breakage wire. The transisters T_1 and T_2 act as switch to discharge the charged capacitor. When the projectile cuts the wire, the switches T_1 and T_2 are closed and the trigger pulse signal is generated across the 50 Ω output resistor. The signal is delayed with adjustable delay pulse generators for controls of the transient recorder, flash x-ray and xenon flash lamp.

2) Flash x-ray System

The 150 kV flash x-ray system of 30 nsec exposure has been constructed for flash x-ray radiography of the projectile using a pulser section of the portable x-ray system (HP model 43501 B). Figure 3 shows the circuit diagram for the flash x-ray system. The pulser section is modified so as to be externally triggered by the pulse produced

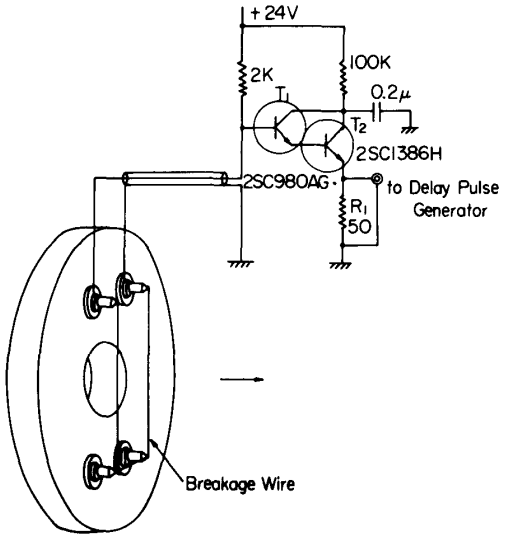


Fig. 2.

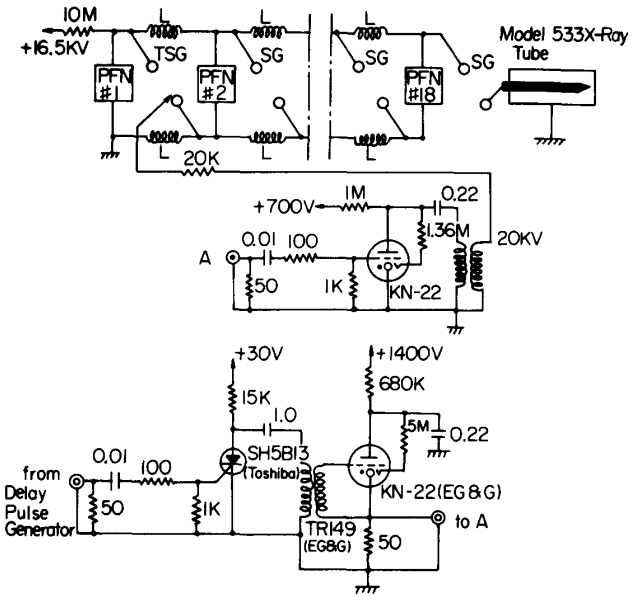


Fig. 3.

Fig. 2. Circuit diagram for breakage wire trigger pulse generator.
Fig. 3. Circuit diagram for flash x-ray system. TSG: trigger spark gap, SG: spark gap, PFN: pulse forming network.

by wire breaking. The HV pulse generator for flash x-ray is a modified Marx-surge circuit. Energy storage elements, pulse forming networks, are connected in parallel during the charging phase of operation. During the discharge phase, the elements are connected in series by the spark gap switches closed and deliver a very high voltage pulse to the x-ray tube (Model 533). The electrical impedance of each module is approximately 5 ohms, thus when in series (discharge mode), total generator impedance is ∿90 ohms. At 150 kV, the peak current, supplied for the x-ray tube is ∿1.7 kA. Other specifications of the system and an example of the flash x-ray radiograph of projectile in flight have been shown in the preceding[6] paper (see Fig. 8).

3) Xenon Flash Lamp

In order to photographically record the time variation of high speed phenomena using a rotating mirror type streak camera with nano second time resolution, an extremely intense light source is required. The present system utilizes a pulsed xenon flash lamp modified from that used by Goto et al.[8] for absorption spectroscopy under shock compression. Details of the lamp configuration and circuit are shown in Fig. 4. The lamp is made of a fused silica tube 3 mm in thickness and 18 mm in inner diameter. Two fused silica windows of 3 mm in thickness are epoxied to both ends of the tube. Special O-ring vacuum

fittings are devised to support the tungsten electrodes of 5 mm in diameter. The O-ring fitting for the negative electrode has a vacuum stopcock to maintain initial evacuation, and later, xenon gas at low pressure of about 10 torr, much lower than the xenon filling pressure of commercial xenon flash lamp. The peak light intensity of capacitor discharge xenon lamp decreases monotonically with increasing filling pressure in this pressure range.[8] A trigger electrode of copper wire 1 mm in diameter is wired helically around the center of the tube. Electrical energy of 0.6-1.0 kJ stored in 125 μF capacitor is discharged through the lamp via a switching ignitron. The light duration of the lamp is about 50 μsec.

4) Continuous Writing Streak Camera

The synchronous streak camera of rotating mirror type used in the explosive shock experiments must precisely control the occurence of shock phenomena to be recorded because the recording can be made only when the image is just present on the film.[4] Observable time window of the streak camera with writing rate of 7 mm/μs is about 15 μs. In shock experiments using a gun it is imposible to control the impact time of the projectile against the target within a several μs. In order to observe optically the shock phenomena, we must use a specially designed continuous writing streak camera of rotating mirror type or

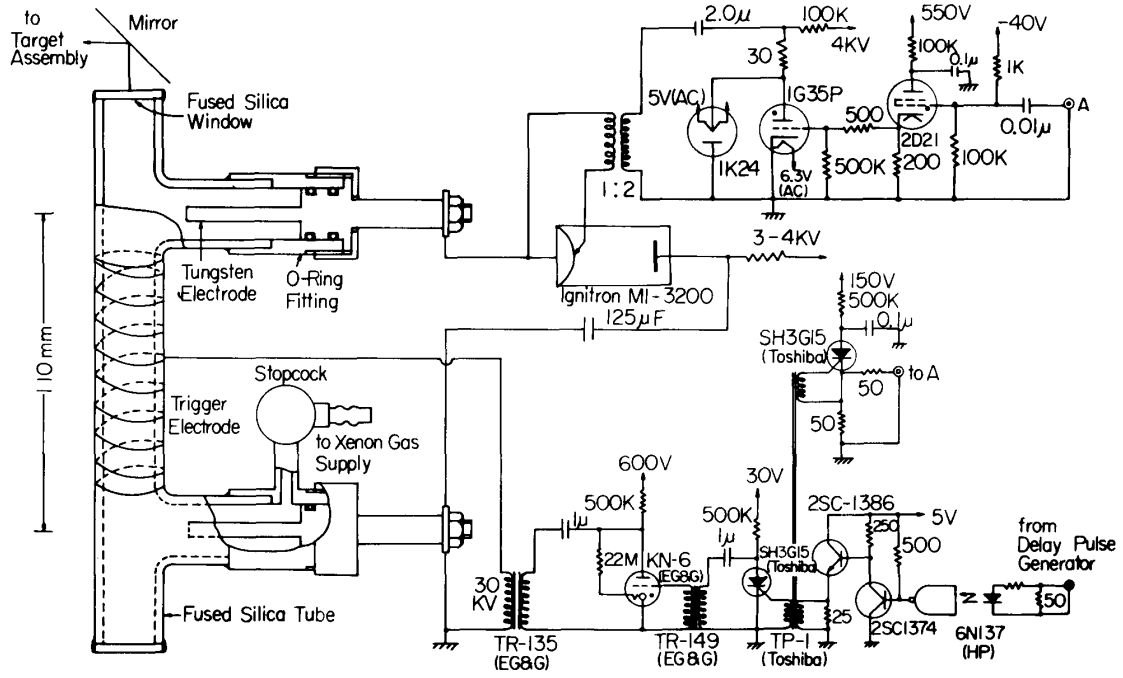


Fig. 4. Xenon flash lamp configuration and circuit.

externally triggered electronic streak camera. Although these streak cameras are now commercially available, they are generally very expensive. Figure 5 shows an optical system for the continuous writing streak camera developed in our laboratory to record non-synchronizable phenomena. An image of the object is focused onto a slit plane by an objective lens L_1 (Nikkor Auto 1:2.5, f = 105 mm camera lens for Hugoniot measurements or f = 63.5 mm fused silica lens for optical absorption spectroscopy). The slit image is relayed to a stationary 35 mm film by a 4.0 magnification relay lens system including a relay lens L_2 (EL Nikkor 1:5.6, f = 210 mm), 45° relay mirror and turbine driven rotating mirror with four mirror faces of 10 mm × 20 mm. The rotating mirror sweeps the slit image on the film. The writing arm between the mirror and film is 536.5 mm in length. This design requires the 45° relay mirror to block a portion of the film plane thus technically eliminating the continuous writing feature of the camera. Presently this mirror is 4 cm wide and blocks 2.4 % of the 1.7 m long continuous writing film record.

The tool steel made, rectangular shaped rotating mirror is manufactured within an accuracy of ±1 μm. Four mirror faces are polished to be optically flat and then aluminized. A pair of magnetic needles of 1 mm diameter and 4 mm length inserted in the mirror are used for measurements of rotation frequency by a pickup coil placed near the mirror. The mirror is directly driven by an air turbine with a maximum revolution of 12,000 r. p. m. (Toshiba Tungalloy Co., LTD. TPF-15A). The mirror turbine assembly have precisely been adjusted in order to have a dynamic balance at maximum revolution by the manufacturer. Because the mirror turbine is currently driven at about 90,000 r. p. m.

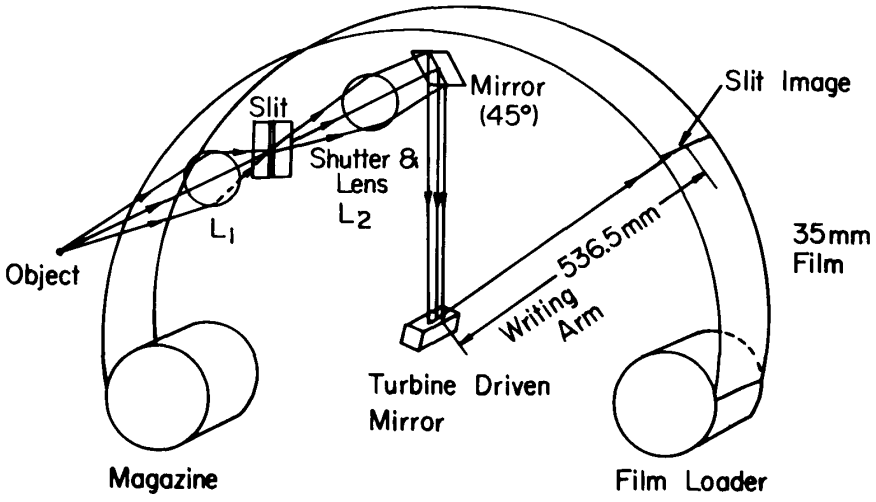
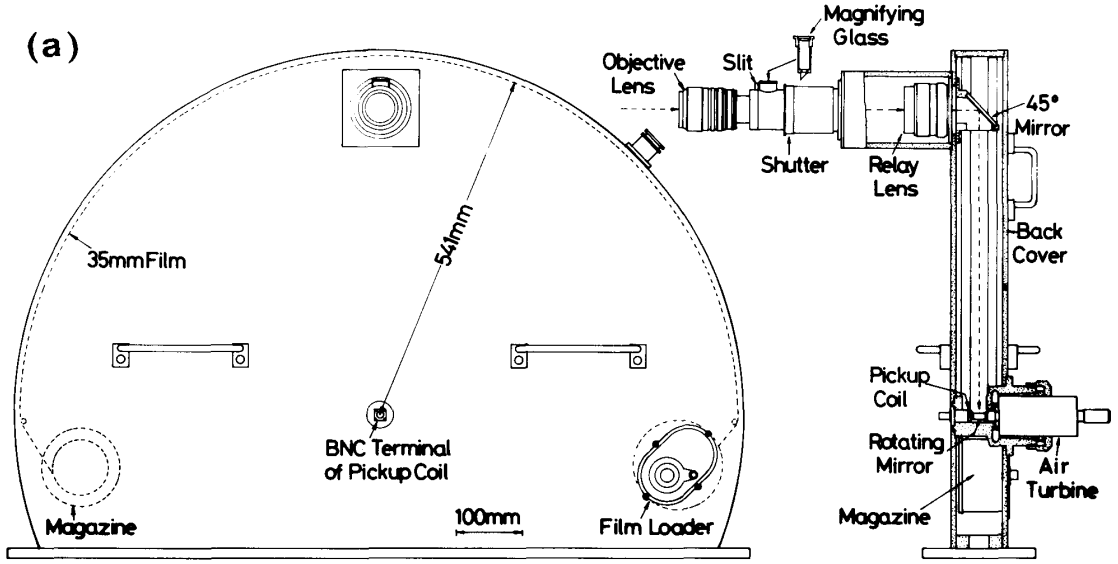


Fig. 5. Optical system for continuous writing streak camera.

by compressed nitrogen gas provided from gas cylinders of 40 ℓ and 150 bar, the writing rate of the camera is about 10 mm/μsec. Figures 6(a) and (b) show the construction and photograph of the streak camera, respectively. The streak camera housing of 1100 mm outer diameter is made of thick steel plates to prevent a vibration due to the high speed rotating mirror. The housing weight is about 130 kg. The objective lens, relay lens and slit are exchangeable in acordance with requirements for various experimental purposes. The slit presently used is 23 μm in width, corresponding to the slit image 92 μm on the film. The resolution of the streak camera is about 20 lines/mm along the dynamic and static directions on the film when EL Nikkor relay lens is utilized. The focusing of the objective image on the slit plane is made by observing a focusing screen inserted at the slit position; the image being examined with a magnifying glass using a



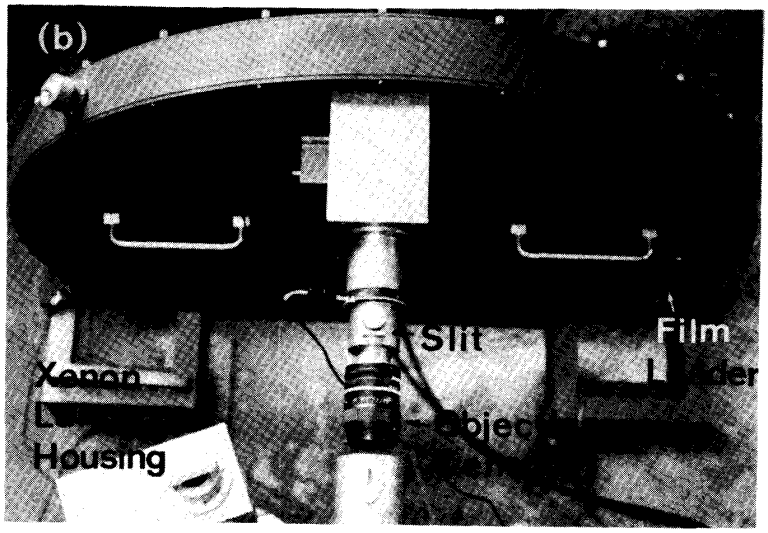


Fig. 6. Construction (a) and photograph (b) of the streak camera.

prism. A reel film of 30 m length in a magazine is loaded in the film track. After the experiment, the exposed part of the film is rolled up in a film cassette of Nikon MZ-1 by a film loader.

In the case of Hugoniot measurements, 35 mm high speed film (Neopan 400 film of Fuji Photo Film Co., LTD.) is used and developed with Pandol developer for 11 minutes at 20 °C. An effective ASA number is 1600. Kodak #2475 film is adopted for the absorption spectral measurements because of higher and flat spectral sensitivity over a range of 300 to 700 nm. An effective ASA number of 4000 is obtained when it is developed with Kodak DK-50 for 9 minutes at 20 °C.

5) Optical System

A refined optical system for measurements of shock compression curve is designed on the basis of the optical system at the shock wave laboratory of California Institute of Technology[9] (Fig. 7(a)). The light from the xenon flash lamp is focused on the target assembly by a lens L_1 (coated achromat 1:4.0, f = 172 mm) via a 45° mirror. The image of the target assembly is focused on the slit plane of the streak camera by a lens L_2 (coated achromat 1:8.3, f = 494 mm) and the objective lens of the streak camera (Nikkor Auto 1:2.5, f = 105 mm). The distance between the target assembly and L_2, or between L_3 and the slit plane is set to be each focal length of L_2 or L_3, respectively. The focus condition of the image on the slit does not depend on the

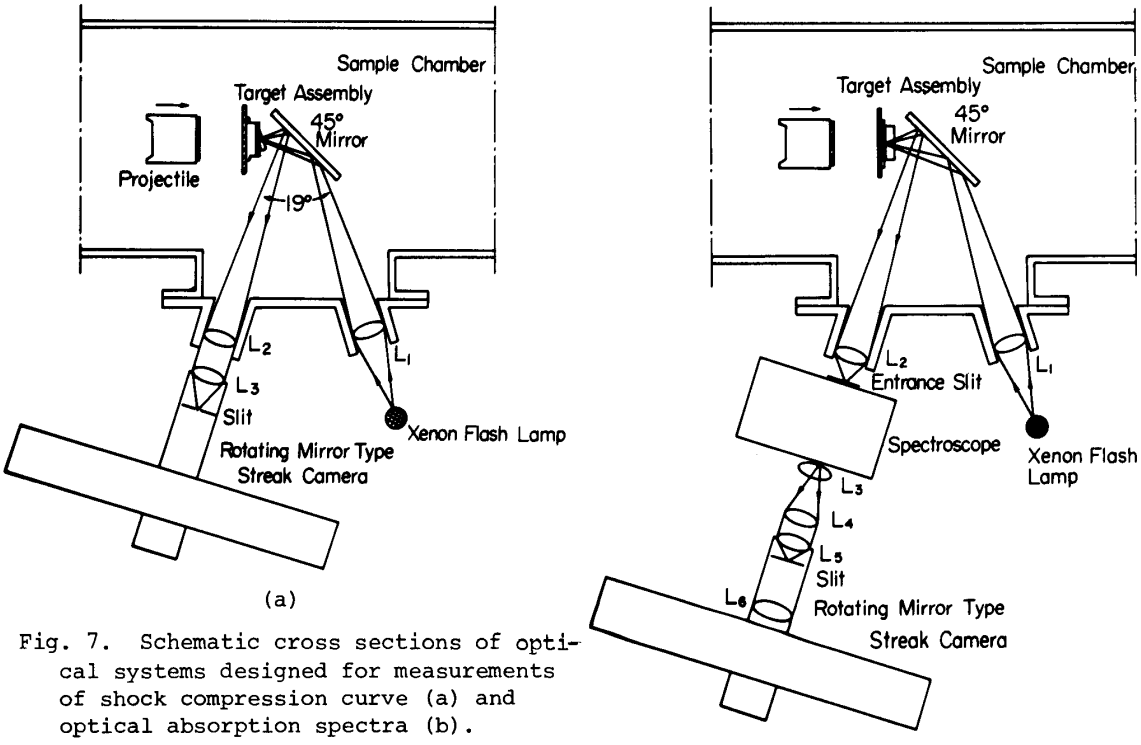


Fig. 7. Schematic cross sections of optical systems designed for measurements of shock compression curve (a) and optical absorption spectra (b).

distance between L_2 and L_3. Because the slit image is relayed to the 35 mm film by the four magnification relay elements including the rotating mirror in the streak camera, the magnification of the image of the target assembly is $\frac{105}{494} \times 4 = 0.85$ on the film.

Time resolved spectral measurement system is designed on the basis of the system developed at California Institute of Technology[8,10] and slightly modified so as to extend the spectral sensitivity, as shown in Fig. 7(b). The light beam from the xenon flash lamp enters the sample chamber via a lens L_1 (fused silica lens 1:4.2, f = 178 mm), is reflected into the sample by the 45° mirror and is reflected internally by a mirror coating on the back of the sample. The reflected light is, in turn, focused on to an entrance slit of a spectroscope with a lens L_2 (fused silica lens 1:1.5, f = 64 mm) and is dispersed by a spectroscope along the slit in the streak camera. The image of the dispersed spectrum is formed at the slit plane in the streak camera by use of lenses L_3 (fused silica lens 1:3.6, f = 152 mm), L_4 (fused silica lens 1:4.8, f = 203 mm) and L_5 (fused silica lens 1:1.5, f = 64 mm). The relay lens L_6 in the streak camera is changed to a fused silica lens with the same focal length (1:5.5, f = 210 mm). A Nikon G 250 monochromator with an interchangeable diffraction grating (300 lines/mm blazed at 500 nm or 300 nm) is modified so as to serve as a simple spectroscope. The spectroscope has a linear dispersion of 12 nm/mm at the exit port, corresponding to the dispersion 8.3 nm/mm on the film in the streak camera. Wavelength calibration for time-resolved absorption spectra taken on the film is obtained with a mercury spectral light source.

Optical alignment of both optical systems is made using a He-Ne laser as a light source. Firstly a dummy target assembly is set on the holding plate and the 45° mirror is suspended on the steel support rod (see Fig. 6 in the preceding paper). Position and angle of the 45° mirror is adjusted so as to reflect the laser beam to the center of the lens L_2 (Fig. 7(a),(b)). The reflected beam is then used for alignment of the spectroscope or streak camera. After the alignment of the system is completed, only the 45° expendable mirror is adjusted with the same procedure before each optical experiment.

III. Measurements of Shock Compression Curve

1) Determination of Shocked State

A shock compressed state of the specimen characterized by pressure ,P, and density ,ρ, is determined from measured shock velocity ,U_s, and particle velocity ,u_p, using the Rankin-Hugoniot conservation

equations;[11]

$$\frac{\rho(P)}{\rho(0)} = \frac{U_s}{U_s - u_p} \tag{1}$$

$$P = \rho(0) U_s u_p \tag{2}$$

The locus $\rho(P)$ determined by a series of shock experiments is called Hugoniot equation of state or, for short, Hugoniot.

Since direct observation of the particle velocity is usually difficult, it is indirectly determined using either the free surface approximation or the impedance match method.[11] The free surface approximation is based on the fact that the free surface velocity, u_{fs}, of the specimen is usually very close to twice the particle velocity, $u_{fs} = 2u_p$, and is widely used for the reduction of Hugoniot data. The method has an advantage in analyzing multiple shock wave structures inherent to phase transition and Hugoniot elastic limit, by observing free surface motion continuously with time. Some details of this method have been described elsewhere.[5]

The impedance match method is another reduction technique to obtain shock wave data. The method is particularly suited for the shock wave experiments using the gun, since the impact velocity of the projectile, V_{imp}, is accurately determined. Figure 8(a) illustrates the concept of the impedance matching with the shock characteristics of the standard material used for the flyer and target plates (curve OA) and of the test specimen (curve OB) in the u_p - P plane. Let us

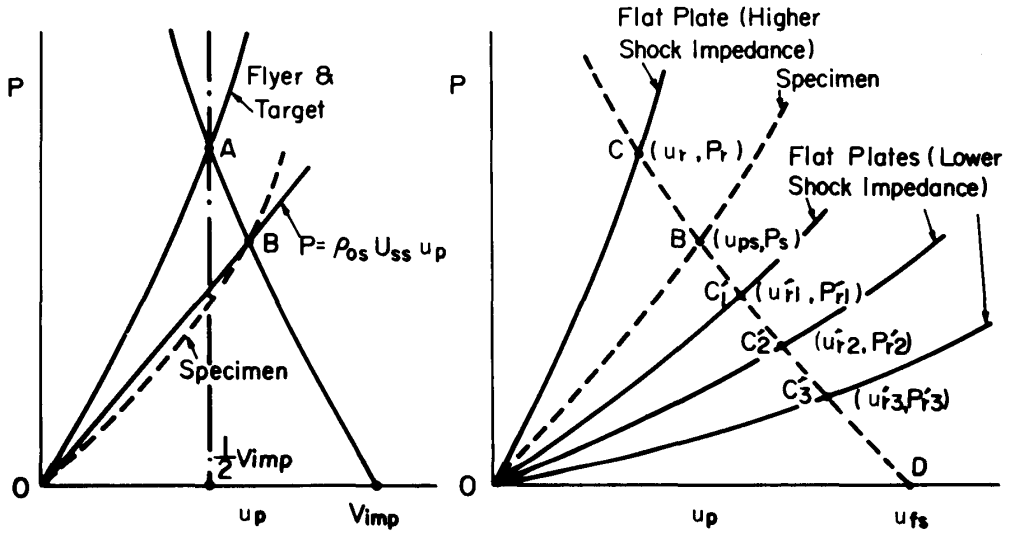


Fig. 8. Particle velocity-shock pressure plane representations of impedance match method (a) and shock reflection technique (b).

consider the case of a symmetric impact (i.e. driver and flyer plates of the same material), where the same state is achieved in the driver and flyer plates, as shown by the point A with $u_p = \frac{1}{2} V_{imp}$. Since the particle velocity and pressure should be the same across the driver plate and specimen interface from the requirements of continuity, the state achieved in the specimen is represented by the cross point of the symmetrically folded characteristic curve AB with respect to $u_p = \frac{1}{2} V_{imp}$ and the line $P = \rho_{0s} U_{ss} u_p$, where ρ_{0s} and U_{ss} are the initial density and measured shock velocity of the specimen. Using the standard target material for which a linear relationship between the shock and particle velocities are accurately known as

$$U_s = C_0 + s u_p \tag{3}$$

the particle velocity is analytically described by following equations:

$$u_{ps} = V_{imp} + \left\{ X - \sqrt{X^2 + 4 s^2 Y} \right\} / 2s \tag{4}$$

$$X = C_0 + \rho_{0s} U_{ss} / \rho_{0t} \tag{5}$$

$$Y = \rho_{0s} U_{ss} V_{imp} / \rho_{0t} s \tag{6}$$

where ρ_{0t} is the initial zero pressure density of the target material.

The concept of impedance matching can also be applied in the analysis of shock reflection technique in which reflected waves originating from the interface of the specimen and a flat plate placed on the upper surface of the specimen bring the specimen into a new shock state. When the shock impedance of the flat plate is higher than that of the specimen, the reflected shock wave compresses the specimen which has already been compressed by the initial shock wave, resulting in intensification of shock pressure. The technique is frequently used in realizing high shock pressures which are hardly attainable by a single shock compression because of the limitation of the impact velocity and shock impedance of the flyer and target material.[12] When the flat plate with lower shock impedance than that of the specimen is used, a rarefaction wave is reflected back into the specimen from the interface and reduces the pressure in the specimen isentropically to a state along the release adiabat. This technique, called as buffer technique, is particularly useful in obtaining the information about the released state when the shock induced phase transition takes place in the initial shock compression.[13]

Figure 8(b) graphically illustrates the procedure for determining the state achieved by shock wave reflection in u_p - P plane. Possible

new state achieved by the reflected shock (or rarefaction) wave from the initial shock state $B(u_{ps}, P_s)$ is represented by the intersecting point $C(u_r, P_r)$ (or $C_i'(u_{ri}', P_{ri}')$) between the characteristic curve CB of reflected shock state of the specimen (or release adiabat curve BD) and shock characteristic OC (or OC_i') of the flat plate meterial because the particle velocity and pressure should be the same across the specimen and flat plate interface from the requirements of continuity. Therefore, the particle velocity and pressure of the reflected state are determined from the measured shock velocity in the flat plate material using the equations (3) and (2), since the shock characteristics of the flat plate material have been accurately known. It is to be noted that the particle velocity of the zero-pressure state on the release adiabat D is equal to the free surface velocity of the specimen ,u_{fs}, obtained by the inclined mirror technique. The release adiabat curve BD from the known initial state $B(u_{ps}, P_s)$ is a locus of release states C_1', C_2', C_3'···· determined by repeating this experiment with different flat plate material. The specific volumes of the states achieved by the reflected shock and rarefaction waves are calculated respectively from the equations,

$$V_r = V_s - \frac{(u_r - u_{ps})^2}{P_r - P_s} \quad , \tag{7}$$

$$V_r' = V_s - \int_{u_{ps}}^{u_r'} (du_p/dP)_s du_p \quad , \tag{8}$$

where V_s is initial shock volume and differential $(du_p/dP)_s$ is made along the release adiabat. The equation (8) is usually called the Rieman integral.[11)]

2) Target Assembly

The inclined mirror technique is utilized for Hugoniot measurements even in the case of the two-stage light gas gun. Shock arrival and continuous displacement of the free surface of the specimen are determined from the extinction of applied illumination reflected from the flat and inclined mirrors placed on the target assembly. The shock state of the specimen is calculated from the measured impact, free surface and shock velocities by use of both the free surface approximation and the impedance match method. The data obtained by both methods are crosschecked with each other.

Figure 9 shows an example of improved target assembly for the inclined mirror technique. A typical dimension of the specimen is 14 mm × 10 mm in lateral extent and 2-3 mm in thickness. Two surfaces

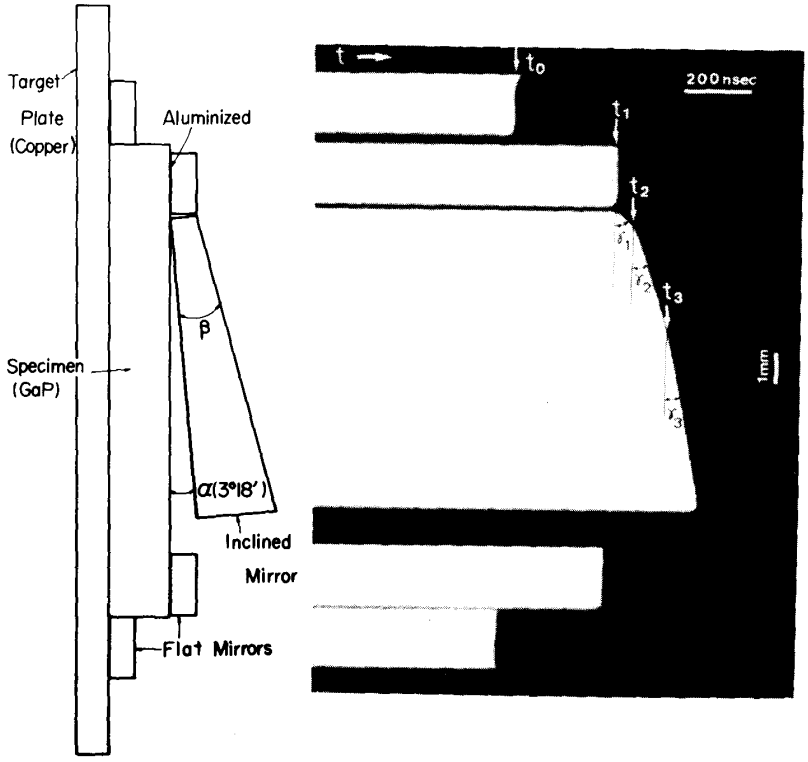


Fig. 9. Target assembly and streak photograph of the inclined mirror technique for GaP. The time of incidence of shock wave into the specimen, and the times of arrival of three successive shock waves (elastic precursor wave, plastic I and II waves) on the free surface of the specimen are indicated by arrows t_0, t_1, t_2 and t_3, respectively.

of the specimen are polished to a flatness and parallelism of ±2 μm with a 5 μm diamond powder for final finish. The inclined glass mirror is shaped to a wedge with an angle of $\beta \simeq 2\alpha$ in order to reflect an incident light almost to the same direction as that of the light reflected by the flat mirrors placed on the target and specimen. A dimension of the inclined mirror is about 9 mm in length and 6 mm in width. The angle α varies from 1° to 5°, depending on the experimental condition. A dimension of the flat mirror is 2 mm × 6 mm in lateral extent and 0.85 mm in thickness. All the specimen and mirrors are fixed on the target plate 26 mm in diameter and 1 mm in thickness with a small amount of epoxy lesin at their margin. Care is taken not to introduce epoxy layer between sample, mirror and target. A flatness of target is also ±2 μm. The flat mirrors on the specimen and target permit the determination of shock velocity in the sample. On the other hand the free surface velocity is measured by the extinction trajectory of the inclined mirror on the sample. An example of the streak photograph for GaP shocked at the impact velocity 2.522 km/sec

is also shown in Fig. 9.

Target arrangements for shock reflection technique are rather simple as shown in Fig. 10. Small pieces of flat plates which are polished on both parallel surfaces are tightly fixed on the upper surface of the specimen with the aid of a small amount of epoxy lesin applied around their margin. For the purpose of intensification of shock pressures, high shock impedance materials such as tantalum or copper are generally used. For release adiabat measurements, use of 2024 aluminum, silica glass, or PMMA (Acrylite or Lucalox) is usually made, in accordance with the impedance requirements. The shock characteristics of these materials are to be obtained from several compilations.[14,15]

Upon each flat plate, a small piece of aluminized glass mirror is placed. An example of streak photograph for GaP is demonstrated in Fig. 10. The target assembly was shocked at the impact velocity 4.072 km/sec. The initial shock pressure of 91.2 GPa in GaP was intensified into 143.5 GPa by the shock wave reflected from the sample and copper plate interface.

Streak record on the film is usually enlarged by more than

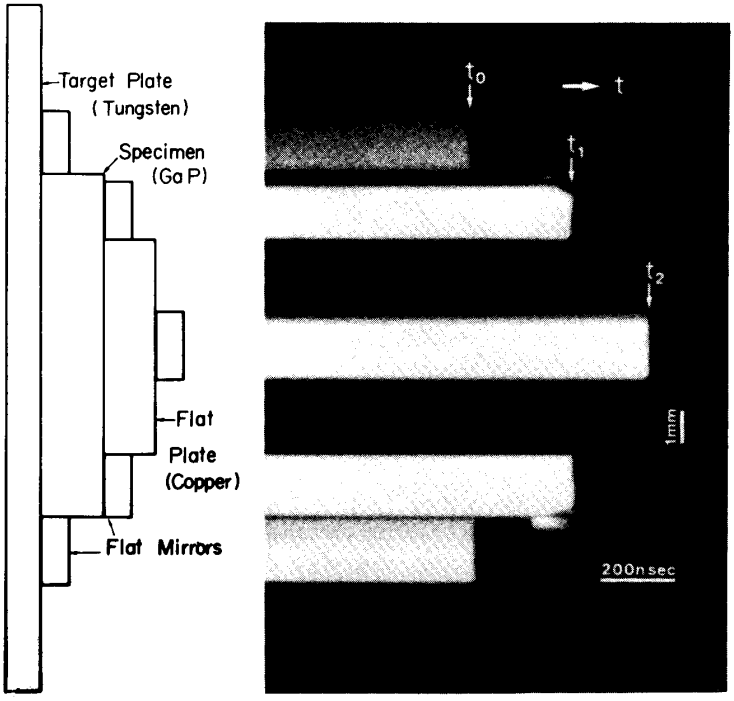


Fig. 10. Target assembly and streak photograph of the shock reflection technique for GaP. The time of incidence of shock wave into the specimen, and the times of arrival of shock wave on the free surface of the specimen and flat plate are indicated by arrows t_0, t_1 and t_2, respectively.

10 times on the photographic paper for accurate determination of shock events. Sometimes the recorded film is directly read by means of microphotometer.

IV. Measurements of Optical Absorption Spectra of Solids under Shock Compression

Experimental techniques for measuring the optical absorption spectra of solids under shock compression offer the opportunity to get microscopic knowledge such as the transition element (cation) coordination enviroment, valency and spin state (high or low spin state) of the transition element and band structure at high dynamic pressure. Figure 11 shows the same target assembly used for the measurements of the optical absorption spectra of Cr^{3+} in Al_2O_3[16] or Fe^{2+} in MgO.[17] The surfaces of the flyer and target plates are polished to be optically flat so as to get smooth shockfront by symmetric impact. However, the shockfront in the target plate is rough on the scale of a wavelength of visible light because of the polycrystallinity of the target. An extra layer of single crystal supphire (Al_2O_3) of 1 mm in thickness is inserted between the sample and target plate in order to smooth out the shockfront during the passage. The transparent sample

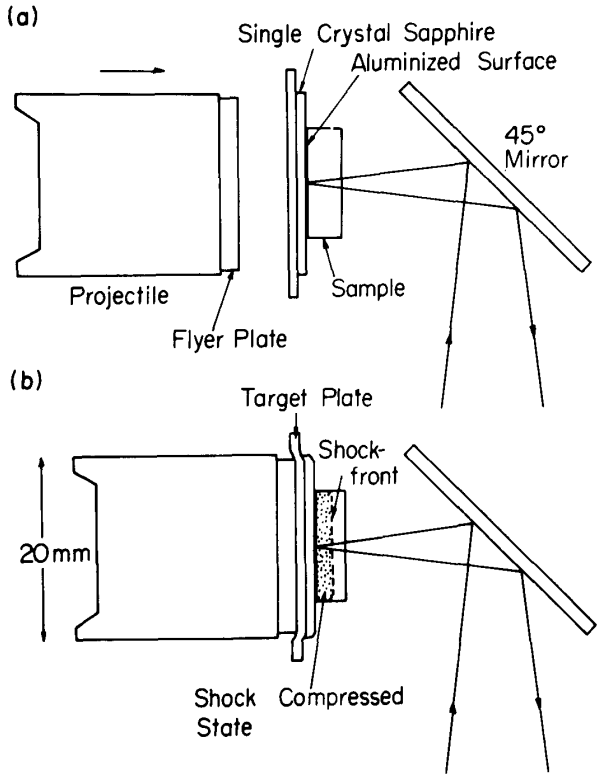


Fig. 11. Target assembly for optical absorption spectral measurement. (a) Before the impact (b) After the impact.

is polished to be optically flat on both sides and then one surface is aluminized so as to form a back surface mirror. The transmission spectrum of the sample is observed with the time-resolved spectrograph. Before the shockfront enters the sample, the absorption is due to the unshocked (zero-pressure) sample. As the shock wave propagates through the sample, the absorption due to the material in the shock compressed region gradually increases at the expense of the material at zero pressure. After the shockfront arrives at the free surface of the sample, we can no longer record the spectrum on the film because rarefaction waves originating from the free surface release the sample from the shock compressed state to the zero-pressure state. This process severely fractures the crystal, making it immediately opaque. Typical example of the time-resolved spectrum of ruby under shock loading has been shown in the previous paper.[16)]

The single crystal sapphire is most popular optical window material with a large shock impedance for high pressure shock wave experiments and proved to be transparent up to 130 GPa.[18)] In the case of isentropic compression it remains transparent up to 500 GPa.[18)] If the optical absorbance of the sample is large, the sample must be polished to be thin so as to record the transmission spectrum on the film. The sapphire window should be placed on the thin sample so as to extend the duration of the shock compressed state of the sample.

The optical absorption spectrum of the sample is recorded on 35 mm Kodak 2475 film. The film is scanned by a microphotometer to read the spectra at various times. The process of the data reduction have been described in detail in the previous reports.[16,17)]

Present authors are now studying pressure effects on the optical absorption spectra of transition metal ions in MgO and Al_2O_3. These results will be reported later on.

Summary

In the present study, the optical measuring system using the continuous writing streak camera and the 1 kJ xenon flash lamp have been developed to obtain precise Hugoniot equation of state and optical absorption spectra of solids under shock compression. Hugoniot and release adiabat are determined with the inclined mirror and buffer techniques, respectively. The shock reflection technique is applied to obtain shock data at higher pressures. The optical absorption spectra of solids under shock compression is observed in the wavelength region of 300 nm - 700 mm using the spectrographic streak camera system.

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