Numerical simulation of shock attenuation in PMMA gap

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Numerical simulation of shock pressure profiles through PMMA gap was carried out using the hydrodynamic code AUTODYN®-2D and the results were compared with the experimental results. The result of the numerical analysis showed higher peak pressures than the experimental values as the gap length increased. Differences were considered as due to the curvature of the detonation front and its two dimensional flow which was assumed as one dimensional in the experiments. Furthermore the longer duration of shock pressure in the simulation might have also the influence of the disagreement.

1. Introduction

A card gap test has been widely used for quantitative evaluation of the shock sensitivity of energetic materials. In this test the shock wave generated by a standard donor explosive is transmitted to the test explosive through an inert gap. The shock sensitivity is obtained as the minimum length of the gap when the detonation within the acceptor fails[1]. The minimum shock pressure for the stable detonation of the test explosive is calculated using a gap length vs. shock pressure calibration curve. However, the calibration curve is usually determined so far by the indirect procedure based on passing time of the shock wave through the gap of several lengths, shock Hugoniot data of the gap material and one dimensional shock wave theory[2]. The verification of the calibration curve is expected in accordance with the direct pressure measurement technique in high pressure region.

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It is the purpose of this investigation to obtain a calibration curve of shock attenuation in polymethyl methacrylate (PMMA) by the direct pressure measurement and compare with the usual method and also with the numerical simulation. The characteristics of shock wave propagation through an inert gap were evaluated by two-dimensional calculation with hydrodynamic code AUTODYN®-2D, and the calculated results were compared with the experimental values.

2. Experimental

2. 1 Experimental arrangement

Fig. 1 shows an experimental arrangement of the shock pressure measurement system. This detonator-donor-gap assembly is same as the shock charging system of the standard card gap test[3]. Pentolite (ρ_0=1650kg·m^{-3}) loaded in polyvinyl chloride (PVC) tube (VP-30) was used as the donor explosive, and PMMA (ρ_0=1185kg·m^{-3}) was used as the gap material. Peak pressures and pressure profiles of shock waves were measured with 50 Ω piezo-resistive manganin gauges (MN4-50-EK) of Dynasen, Inc.. The gauge is photo-etched from a single foil and encapsulated between two 25 μm thick layers of kapton using epoxy resin as gauge filler and binder. The manganin grid size is 3.8×3.8 mm and about 10 μm in thickness[4].

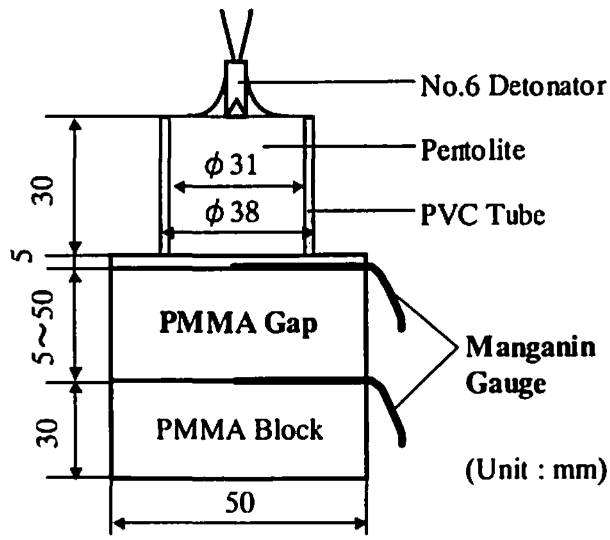

Fig. 1 Experimental arrangement of shock attenuation in PMMA

A 5 mm thick PMMA plate was put between the gauge and donor pentolite to protect the gauge from the short-circuiting[5)6)]. These gauges, protection plates and PMMA gap were glued with epoxy resin and pressed to fix.

2. 2 Measurement principles

The peak pressure of the shock wave at several gap lengths i.e. the shock pressure after several distances from the interface with donor pentolite were measured using manganin gauges embedded between 5 mm PMMA plate and PMMA gap with desired length. Two manganin gauges were also used to detect the arrival of shock waves and shock passing times during several gap lengths were determined simultaneously for usual calibration.

2. 3 Results

Pressure profiles of shock waves in PMMA are shown in Fig. 2 and from the peak pressure vs. gap length plots the peak pressure at each distance from the donor pentolite was obtained as following formula[7)]:

$$P = 10.9\exp(-0.052l) \quad (5 < l < 55) \tag{1}$$

where P is peak pressure (GPa), l is gap length (mm). Above formula is applicable only in the range of the gap length from 5 to 55 mm due to the pressure cover range of the 50 Ω manganin gauge.

On the other hand the peak pressure vs. gap

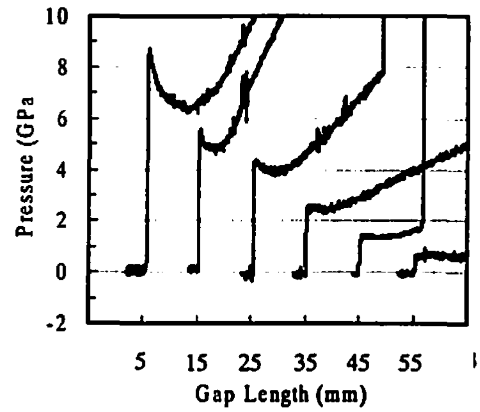

Fig. 2 Pressure profiles of shock waves in PMMA gap measured by manganin gauges

length curve was obtained by the usual method using the shock passing time in each length of PMMA gap with the shock Hugoniot data of PMMA which was reported by Deal as follows[7)8)]:

$$P = \frac{0.38 - 0.0069l}{(0.19 + 0.0028l)^2} \quad (5 < l < 50) \tag{2}$$

Two calibration curves are in good agreement in the range of 5 to 40 mm within the experimental error.

Shock Hugoniot of PMMA can be obtained from the experimental values by Eq. (2) with the conservation of momentum of one dimensional shock wave and a linear least squares fit as:

$$U_S = 2.76 + 1.42U_P \tag{3}$$

Although the physical characteristics of PMMA differ by polymerization conditions the above formula coincides very much with the reference data which was reported by Deal as following formula[8)]:

$$U_S = 2.88 + 1.38U_P \tag{4}$$

3. Numerical analysis

3. 1 Conditions of analysis

Although one-dimensional flow of shock wave is assumed in the experimental determination of peak pressure the shock front is considered as not being flat and it has a curvature because the donor pentolite is initiated by an electrical detonator. In this section shock pressure through PMMA gap was also calculated with the hydrodynamic code AUTODYN®-2D developed by Century Dynamics Inc. and the result of two-dimensional calculation

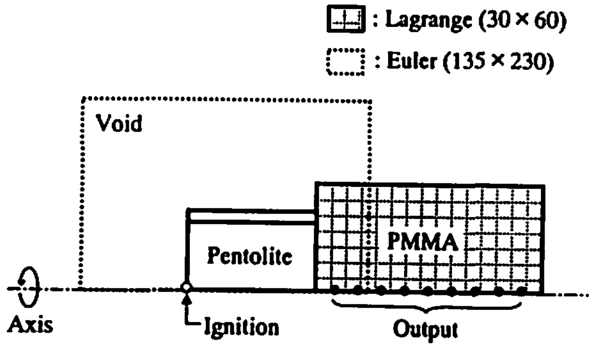

Fig. 3 Configuration of the analysis model of shock propagation

is carried out.

AUTODYN®-2D is based on the conservation laws of differential equations in the continuum mechanics and the explicit finite difference method[9]. Fig. 3 shows the schematic view of the analyzed system in this study and the calculation was carried out with two-dimensional axial symmetry model. PMMA and PVC were assumed as inert solids and pentolite was as high explosive. To compare with the manganin gauge results Lagrangian coordinate system was applied to PMMA and calculated points were arranged in this system. Eulerian coordinate system was applied to detonating pentolite because of the probable over distortion of Lagrange mesh.

Parameters of each equation of state (EOS) applied in this study are described in Tables 1 and 2[10,11]. JWL EOS was used as EOS of pentolite and Mie-Grüneisen EOS was used for PMMA and PVC. As the attempt to apply JWL EOS to AUTODYN®-2D has been reported[12,13] the parameters of JWL EOS were obtained by fitting the detonation characteristics with KHT EOS in this analysis. Eq. (4) was used as the shock Hugoniot for Mie-Grüneisen EOS.

3. 2 Results and discussions

Pressure-time histories at each output point of Lagrange coordinate system in PMMA were calculated and peak pressure vs. gap length plot was made as well as experimental result. A typical calculated pressure profile at 5 mm from the donor pentolite is shown in Fig. 4 with the experimentally measured profile. Although the pressure rise is less sharp than the measured profile the peak pressure shows a very good agreement.

Fig. 5 shows the gap length vs. pressure curve, i.e. the calibration curve of the gap test and the shock attenuation in PMMA. The calculated peak pressures give a coincidence in the high-pressure region with the experimental values. However, they show higher peak pressures than the experimental ones as gap length increases. The difference between the experimental results and the calculation was considered as following reasons;

(1) Shock front is not flat and has a curvature despite one-dimensional shock wave is assumed in the analysis of experimental data.

(2) Shock wave does not enter to the gauge with a

Table 1 C-J and JWL parameters of detonating pentolite

Explosive	C-J				JWL				
	P [Mbar]	D [cm·μs⁻¹]	E_0 [Mb·cal·cm⁻²]	ρ [g·cm⁻²]	A [Mbar]	B [Mbar]	R_1	R_2	ω
Pentolite	0.232	0.746	0.0889	1.65	8.710	0.194	5.513	1.461	0.335

$$P=A\left(1-\frac{\omega}{R_1V}\right)\exp(-R_1V)+B\left(1-\frac{\omega}{R_2V}\right)\exp(-R_2V)+\frac{\omega E}{V}$$

Table 2 Mie-Grüneisen parameters of PMMA and PVC

Material	ρ_0 [g·cm⁻³]	C [cm·μs⁻¹]	s	Γ
PMMA	1.185	0.285	1.37	0.97
PVC	1.376	0.231	1.47	1.00

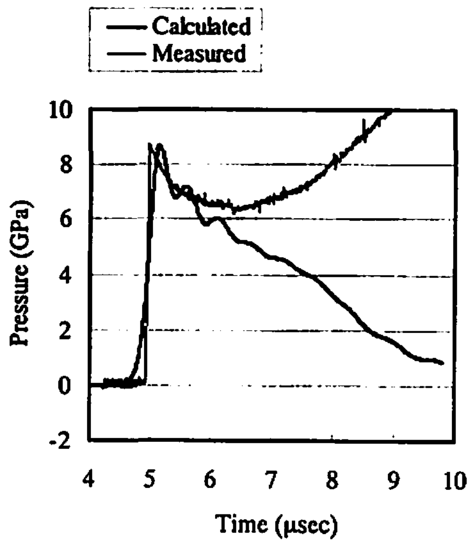

Fig. 4 Comparison of measured and calculated shock pressure profiles

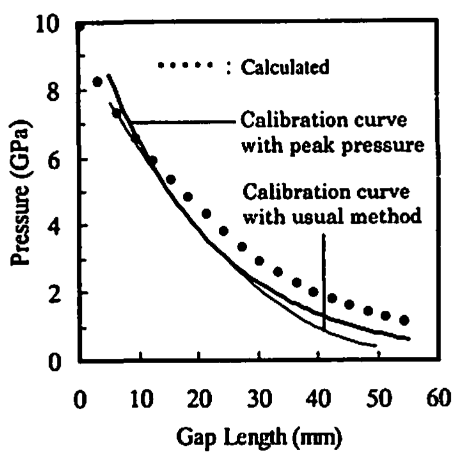

Fig. 5 Shock attenuation in PMMA computed by AUTODYN®-2D compared with experimental results

perpendicular angle.

(3) Physical characteristics of materials in high pressure region do not fit the real values and appropriate values are needed to adjust them.

Fig.6 shows the isobar diagrams of the shock wave propagation through pentolite and PMMA gap, and the pressure level is given as a contour image in the figure. It is obvious that the detonation/shock front has a curvature because of the point initiation of the electric detonator and rarefaction wave from the side wall. Fig. 7 shows the high speed camera recordings of shock wave through PMMA gap with 4 μsec steps which were taken at 1000000 fps by the Cordin model-124. The shock front curvature is observed and gives a very good representation with the AUTODYN® simulation. Regarding (2) and (3), discreet experimental preparation and a further investigation on physical model will be desired.

4. Conclusions

From the experimental and numerical analysis, following conclusions can be drawn:

(1) The calibration curve was determined in a form of exponential function as $P = 10.9 \exp(-0.052\, l)$ by the direct pressure measurement, and it showed a good agreement with the usual method which was determined with shock Hugoniot.

(2) As a result of the numerical analysis with AUTODYN®-2D, the attenuation of the shock pressure in PMMA was more gradual than the experimental result. This may be because of the parameters of the material model and/or the assumption of one-dimensional shock wave in the experiment.

(3) From the high-speed camera records, the curvature of the shock front was observed and it was successfully reproduced by the simulation.

Acknowledgment

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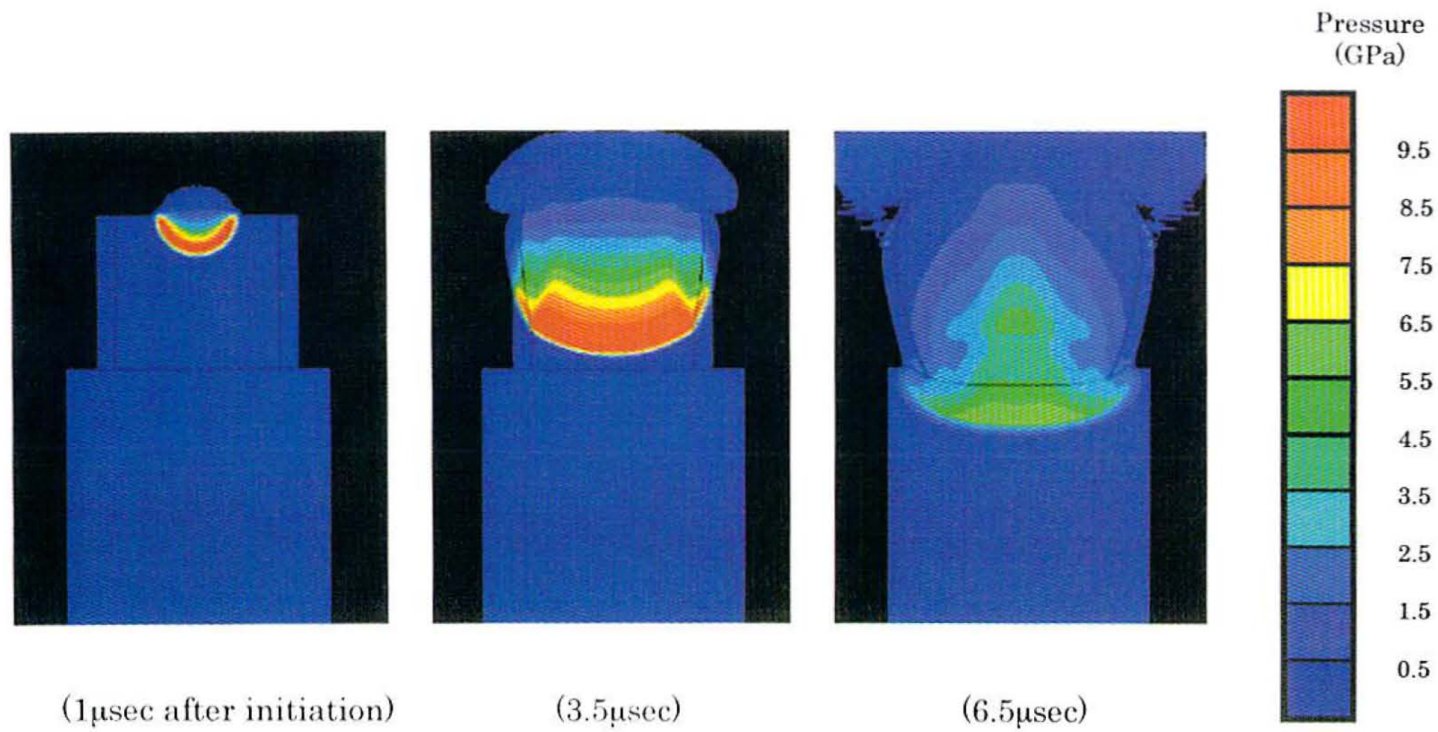

Fig. 6 Pressure contours of shock propagation through PMMA gap calculated with AUTODYN®-2D

Fig. 7 High-speed camera photographs of shock wave propagation in PMMA gap

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