Study on low velocity detonation phenomena in Nitromethane

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ABSTRACT
In detonation of an explosive, there are two forms, high velocity detonation (HVD) and low velocity detonation (LVD). For example, it is known that the detonation velocities of methyl nitrate are 6700m/s in HVD and 2500m/s in LVD. In a liquid explosive, the highest pressure of LVD changes with the type of explosive and conditions, is a few GPa and has destructive power equivalent to HVD. It is important also for security to get to know the actual condition of LVD. Moreover, it is important that the performance of explosives is completely understood to control HVD, LVD, and deflagration, and to predict the behavior of the explosive.

1. INTRODUCTION

Nitromethane (density 1131 ~ 1137 kg/m^3) is a typical liquid explosive, and since it is homogeneous and isotropic, the character is simple when compared with a heterogeneous solid explosive. Although it has the explosion power exceeding TNT, it is only used as an organic composition material in the industrial field as it is relatively insensitive. It is used as a paint solvent because the ignition point is comparatively high, 44 degrees C.

In this research, in order to understand HVD and LVD characteristics of NM, air bubbles and a shock wave are observed optically using a high-speed video camera. The mechanism of cavitation bubble generation by the precedent shock wave, which is the main feature of the LVD phenomenon, is solved based on the data.

The generation of the cavitation, which is an important factor for LVD, was found by optical observation. The action of a precedence shock wave and detonation wave was also observed, and each velocity was calculated with the streak and framing photographs. This result showed that the distance that the detonation wave exists became shorter as Gap length increased, because the incidence pressure lower.

2. EXPERIMENTAL SETUP AND NUMERICAL ANALYSIS

2.1. OPTICAL OBSERVATION AND MEASUREMENT OF DETONATION VELOCITY

The optical observation that uses the shadowgraph system [1,2] was used to evaluate the shock wave and detonation wave propagating. The shadowgraph system used in this study is

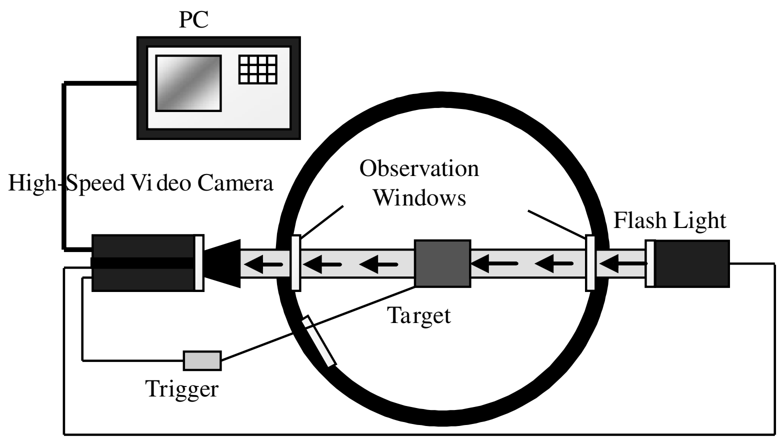

Figure 1 Shadowgraph system for optical observation.

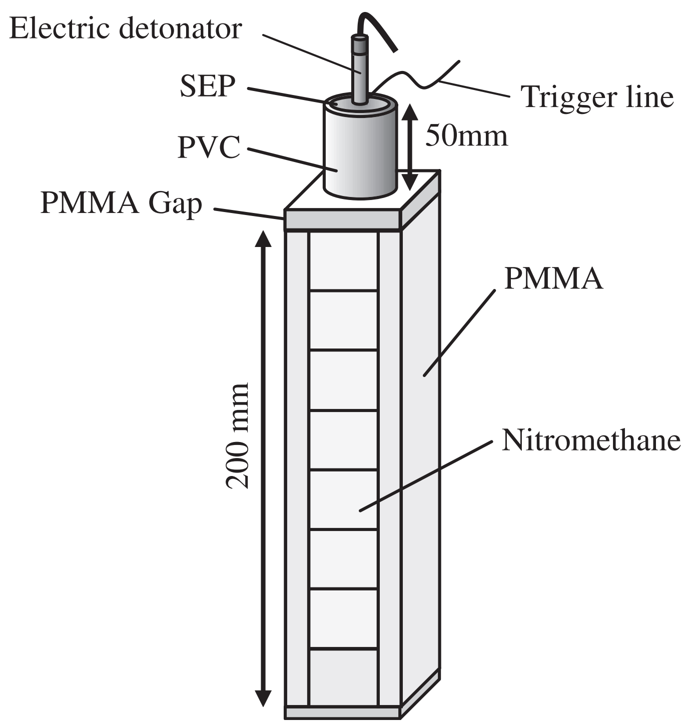

Figure 2 Schematic illustration of an optical observation for the framing photography.

shown in Figure 1. This system uses a technique, also called direct projective technique, in which the shadow of the light observed and projected by density change on a screen. The shadowgraph method used for visualization of a shock wave and detonation wave or the motion of a wave has been used for many years.

The shadowgraph system and a high-speed video camera (product made from Shimadzu Corp) were used to observe the shock wave and detonation wave propagating in NM.

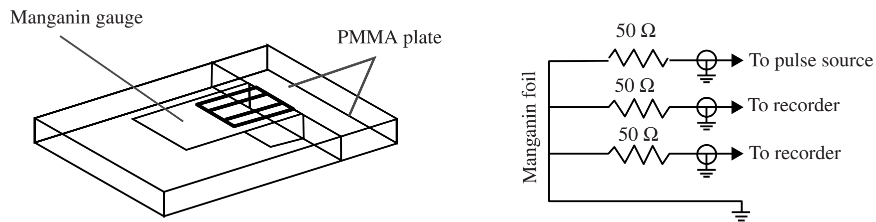

Figure 3 Schematic of pressure measurement system.

The velocity of a shock wave was obtained by taking a framing photography using the shadowgraph method. The schematic illustration of an optical observation for the framing photography is shown in Figure 2.

A PVC pipe, (30 mm of diameters of inner) with a height of 50 mm was loaded with 50 g of high explosives SEP (made by Asahi Chemical Chemicals, detonation velocity about 7,000 m/s, density 1310 kg/m^3) as booster. The NM container is a 30 mm × 30 mm box form inside, and an each side is constituted from PMMA (density of 1185 kg/m^3). NM is poured into it, and a booster is put on a container through PMMA Gap, and it is detonated with a No. 6 electric detonator.

2.1.1. Variation in velocity by PMMA gap length

The experiments are performed while changing the length of PMMA Gap with 0, 1, 2, 5, 10, 20, 50, 100 and 200 mm. NM is poured in a container and we observed the relation between the length of PMMA Gap and shock wave velocity and the detonation velocity. Water is poured in a new container, and it is tested under the same condition.

2.2. MEASUREMENT OF INCIDENT PRESSURE TO NM

2.2.1. Manganin gauge

We have conducted the experiment to measure the peak pressure of shock wave using manganin gauge. Manganin gauge and its measurement system are shown in Figure 3. Impedance of manganin gauge is 0.3~0.5, it was designed by Mashimo et al. [3,4]. Manganin gauge consists of a 6?m-thick manganin foil (83.5wt.%Cu, 11.5wt.%Mn, 4.4wt.%Ni) of 0.5~1.0 mm in width, and after, manganin gauge is set to the PMMA plate (75 mm × 75 mm). The measurement system in this experiment consists of oscilloscope (LeCroy Co. Ltd., Japan) and pulse power source which supply the current (5A~10A) for 50 ?µs. The circuit of the gauge is shown in (b) of Figure 3. The first line is connected to the pulse power source, the second and third line is connected to the oscilloscope and last line is set to the earth. The peak pressure of shock wave is calculated as follows:

$$\Delta R / R_0 = -0.0329 + 0.0276\sigma_x \tag{1}$$

The peak pressure of shock wave is measured from the correlation between the resistance change and shock stress. The voltage measured by oscilloscope is converted into the resistance change ($\Delta R/R_0$) because of constant current from pulse power supply.

2.2.2. Pressure measurement experiment

The schematic of pressure measurement experiment is shown in the Figure 4. Although it is almost the same as Figure 2, the PMMA block (cross section is 70 mm × 70 mm, thickness

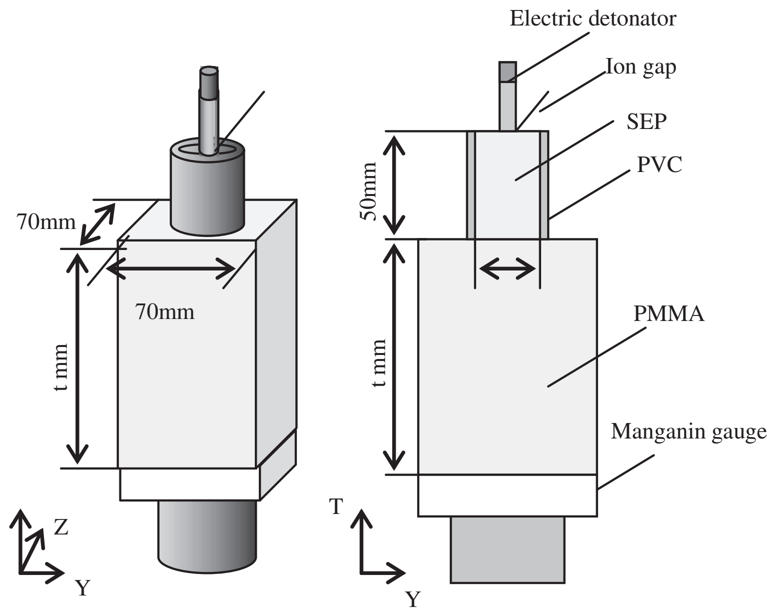

Figure 4 Schematic of Pressure measurement experiment.

Table 1 Thickness of PMMA block

Experiment	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Thickness t (mm)	1	2	5	10	20	30	40

is *t* mm) is set to the lower part. The manganin gauge was set so the measurement part might be placed on the main axis of an explosive. Thickness t was varied as shown in Table 1 and the pressure was measured in each case.

2.2.3. Numerical analysis

The incident pressure to NM could predicted by manganin gauge. And the phenomenon for an explosion and the propagation of shock wave in PMMA are evaluated by means of LS-DYNA 3D. Figure 5 is presented to the numerical simulation model. This simulation model is 1/4 three-dimensional cylinder model. In boundary condition, initial velocity has 1711 m/s at the left side of SEP explosive. We applied the constrained condition for the x, y, z axis so that a translational and rotational motion can not happen when explosion is occurred in explosive container.

In this numerical analysis, we applied Jones-Wilkins-Lee (JWL) equation of state [1] for the explosive. JWL coefficients are given in Table 2. Expression of JWL equation of state is described as follows:

$$P = A\left[1-\frac{\omega}{VR_1}\right]\exp(-R_1V)+B\left[1-\frac{\omega}{VR_2}\right]\exp(-R_2V)+\frac{\omega E}{V} \tag{2}$$

$V = \rho_0$ (Initial density of an explosive)/ρ (Density of detonation gas), P is Pressure, E is Specific internal energy, and A, B, R_1, R_2, ω are JWL parameters.

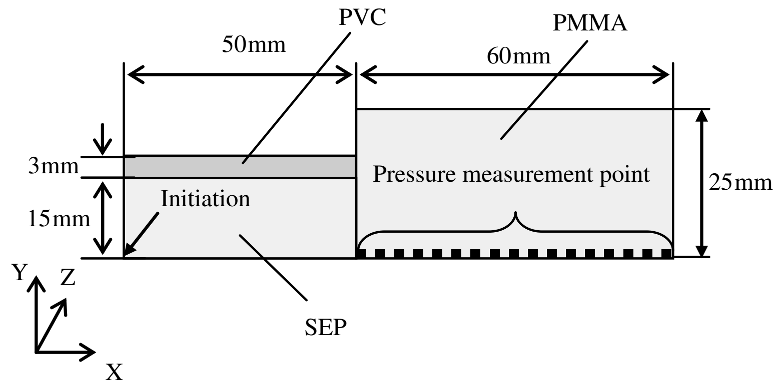

Figure 5 Numerical simulation model.

Table 2 JWL parameter of SEP

	A (GP_a)	B (GP_a)	R_1	R_2	
SEP	364	2.31	4.3	1.00	0.28

Table 3 Mie-Grüneisen parameter of PMMA and PVC

	ρ_0 (kg/m^3)	c_0 (m/s)	s	Γ_0
PMMA	1180	2260	1.82	0.75
PVC	1376	2250	1.505	0.40

Accordingly, we have applied Mie-Gruneisen equation of state for PMMA and PVC. Mie-Gruneisen equation of state is given as follows and the parameters of PMMA and PVC are shown in Table 3.

$$P = \frac{\rho_0 {c_0}^2 \eta}{(1-s\eta)^2}\left[1-\frac{\Gamma_0 \eta}{2}\right]+\Gamma_0 \rho_0 e \tag{3}$$

$\eta = 1-\rho_0$ (initial density of the medium) /ρ (density of the medium), P is Pressure, e is Specific internal energy, and c_0, s are Constant of material, Γ_0 is Grüneisen coefficient.

3. RESULTS AND CONSIDERATION

3.1. OPTICAL OBSERVATION AND MEASUREMENT OF DETONATION VELOCITY

Framing photographs [2] were obtained by optical observation using the high-speed video camera. The framing photographs in the case of PMMA Gap length of 10 mm is shown in Figure 6 (a). When the shock wave releases from the inside of container side wall into NM, the shock wave collides and cavity bubbles occur in the central part. The reaction in the liquid containing this cavity bubble causes LVD. As a role of a cavity bubbles, it's generally understood that the reaction by the shock of the mutual collision at the time of the micro jet of a liquid jumping into cavity bubbles [5].

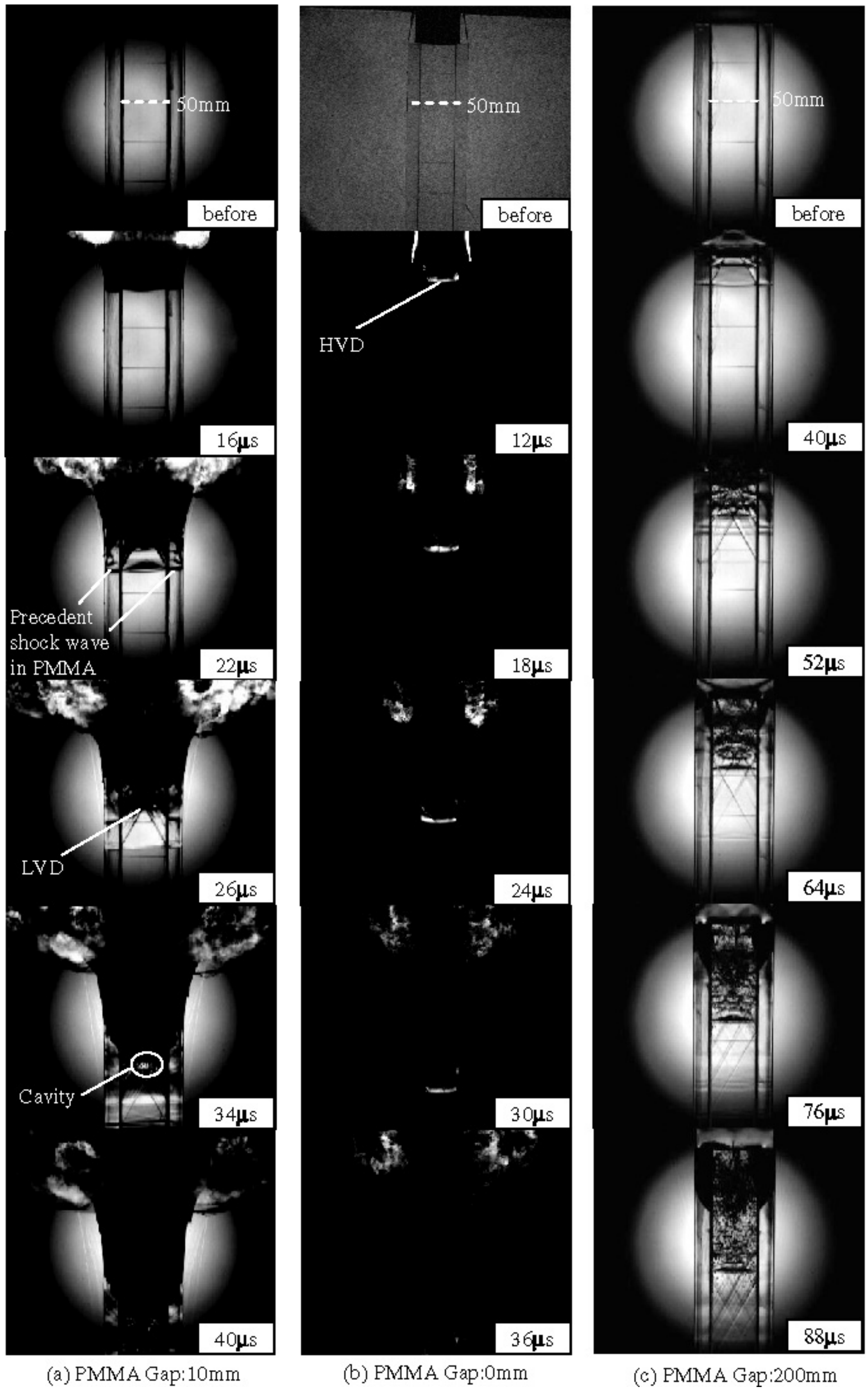

Figure 6 Framing photographs of Nitromethane.

The framing photographs in the case of that PMMA Gap length is 0 mm and 200 mm are shown in Figure 6(b) and Figure 6(c). In the case of that PMMA Gap length is 0mm, since the shock wave produced by detonation of SEP entered into NM directly and high pressure

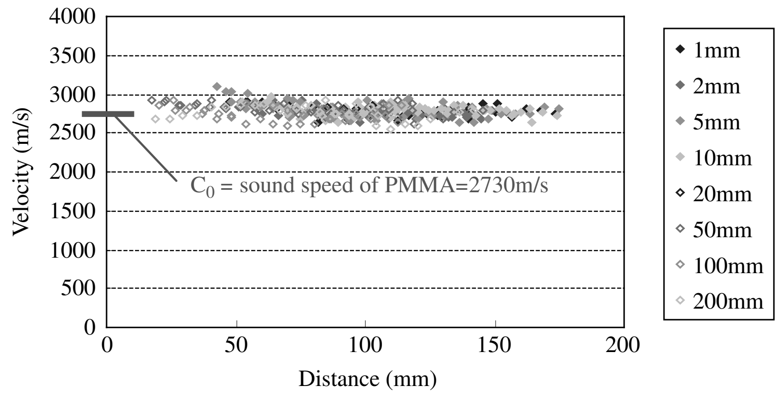

Figure 7 The relation between the velocity of precedent shock wave and the distance from PMMA gap.

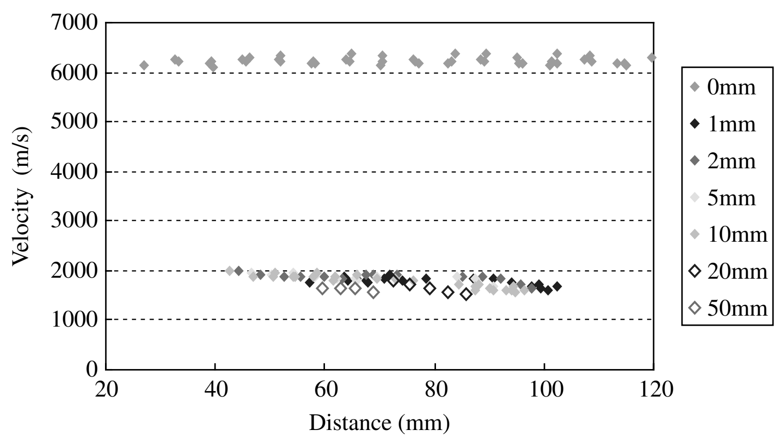

Figure 8 The relation between the velocity of detonation wave and the distance from PMMA gap.

was applied, HVD (the usual detonation) was happened. In the case of that PMMA Gap length is 200 mm, since the pressure of incidence is low, LVD is not found.

The precedent shock wave velocity and low velocity detonation are found from framing photographs and streak photographs. The relation between the velocity of precedent shock wave and the distance from PMMA Gap are shown in Figure 7. This graph shows that the velocity of precedence shock wave is about 2700–2900 m/s, and the velocity converged sound velocity of PMMA (2730 m/s). The relation between the velocity of detonation wave and the distance from PMMA Gap are shown in Figure 8. This graph shows that the velocity of detonation wave is about 1,600–1,700 m/s. The detonation wave propagates at a velocity higher than the sound velocity of NM (1350 m/s). So this is low velocity detonation (LVD).

The velocity of the reaction of LVD starts and finishes were not changed by Gap length. However, the range which can observe LVD is small as Gap length becomes long from Figure 8. And the distance which detonation wave maintains becomes short since incident pressure is attenuated as PMMA plate becomes thick.

In the case of PMMA Gap length of 0 mm, since the shock wave produced by detonation of SEP entered into NM directly and high pressure was applied, HVD (the usual detonation)

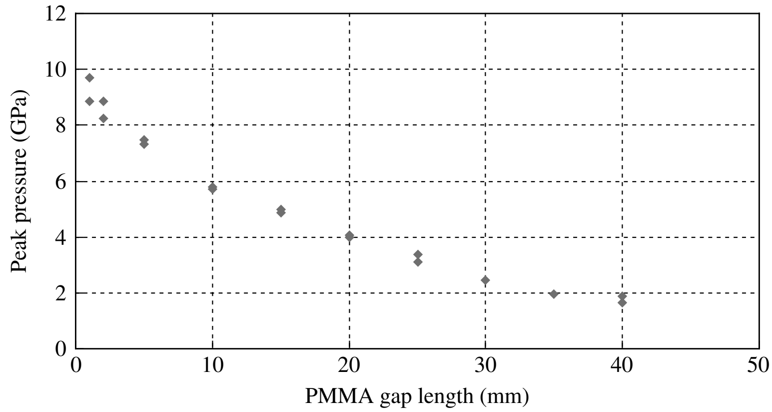

Figure 9 Pressure measurement experiment result.

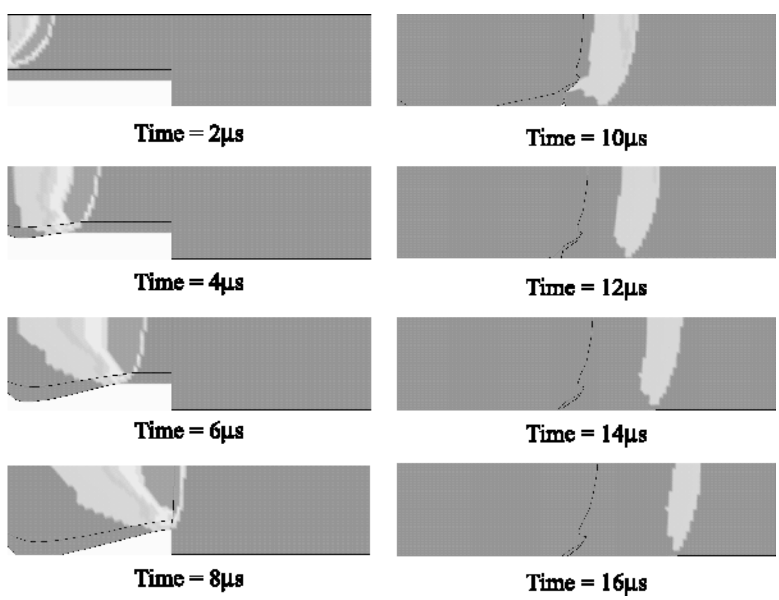

Figure 10 Pressure distribution of shock wave.

was happened. The velocity was about 6300 m/s. The detonation velocity of NM is 6300 m/s and the variation of the calculated velocity can be said to be within the limits of the measurement error.

3.2. MEASUREMENT OF INCIDENT PRESSURE TO NM

3.2.1. Manganin gauge

The result obtained by measurement of pressure experiment is shown in Figure 9. Pink points in Figure 9 show the peak pressure value at the front of shock wave. As shown in Figure 9, pressure is attenuated as PMMA plate becomes thick. Although the 1mm point shows about 10 GPa, since the detonation pressure of SEP is 15.9GPa, it turns out that it is attenuating considerably when propagate in PMMA.

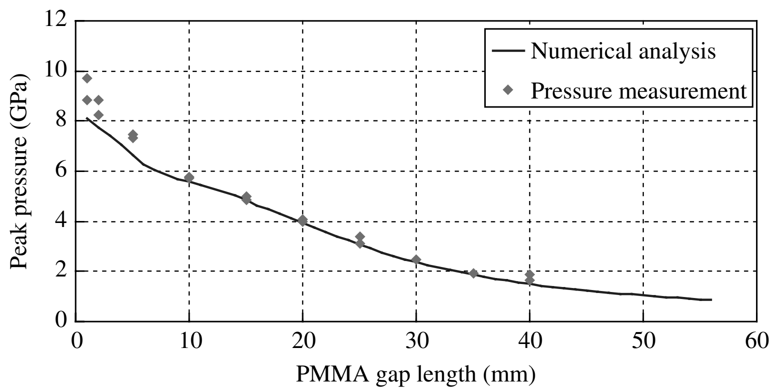

Figure 11 Numerical analysis and pressure measurement experiment result.

3.3. NUMERICAL ANALYSIS

The pressure distribution of shock wave that obtained by numerical analysis is shown in Figure 10.

After 4 µs from the initiation of explosive SEP, the detonation wave edge propagates inside explosive SEP about 30 mm from the initiation face, and the maximum pressure is about 14.6 GPa. After 8?s from the initiation of explosive SEP, the shock wave generated by the detonation wave propagates in PMMA. The shock wave edge exists 1 mm point from the edge in PMMA and the maximum pressure is about 9.0 GPa. After 10?µs from the initiation of explosive SEP, the pressure of shock wave is attenuated. The shock wave edge exists 20 mm point from the edge in PMMA and the maximum pressure is about 4.0 GPa. After 14 µs from the initiation of explosive SEP, the pressure of shock wave is more attenuated. The shock wave edge exists 40 mm point from the edge in PMMA and the maximum pressure shows about 1.7 GPa.

The pressure curve obtained by numerical analysis is shown Blue plots in Figure 11. The pressure curve is continuous.

The result of the measurement of pressure experiment and numerical analysis are compared. As shown in Figure 11, both results are almost corresponding but some errors exist.

This is attributed to the fact of experimental error in the pressure measurement experiments and disagreement of the condition in the numerical analysis. In the numerical analysis, the size of the elements of numerical analysis model is reduced, and it is enumerated to reduce the time interval, and the contact condition on the boundary side of each part is made more appropriate. It is important to improve these, and to improve the reproducibility of the numerical analysis. Moreover, it is necessary to perform experiment on Table 1 conditions several times, and to obtain more accurate data.

4. CONCLUSION

In the experiment of optical observation, the action of a precedent shock wave and detonation wave in nitromethane was observed, and the respective velocities were found with the framing photographs. Generation of the cavitation which is an important factor for low velocity detonation generating was clarified by optical observation. The distance required for detonation wave maintains becomes smaller as Gap length increases longer that is, as the incidence pressure becomes smaller.

In the pressure measurement experiment, the relation between the length of PMMA and shock wave pressure were shown. As a result of conducting numerical analysis, experimental and numerical result are in good agreement.

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