Article

An investigation on under water sympathetic detonation for high explosives

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Sympathetic detonation is one important element for the initiation of explosives. The sympathetic detonation for high explosives has been investigated for the last several decades[1]. However, most experiments were conducted in the atmosphere, while the phenomenon of underwater sympathetic detonation was only slightly investigated.

The underwater sympathetic detonation of Composition B (RDX: 64%, TNT: 36%, Detonation velocity 7,900m/s) was investigated. The distance between the donor explosive and the receptor explosive was varied in the water. In order to investigate the basic characteristics of the underwater sympathetic detonation of the high explosives, the underwater sympathetic detonation and the shockwave in the water was captured by a high-speed camera (HADLAND PHOTONICS, IMACON790). In addition, the pressure of sympathetic detonation is measured using a Manganin gauge (KYOWA Electronic INSTRUMENTS CO. SKF-21725). The pressures in the cases of complete and incomplete explosions were measured.

The numerical simulation was used to investigate the sympathetic detonation more extensively. The numerical simulation was performed by solving the equations of mass, momentum and energy under Lagrange coordinate system and the equation of state of explosives. In the numerical simulation of sympathetic detonation it was very important to investigate the treatment for the reaction of explosives. Many researchers have proposed the burn technique, which calculate the reaction rate of explosives. We used Lee-Tarver model because the burn technique incorporates the ignition and growth concept of shock initiation for high explosives.

The results of both the experiments and the numerical simulations are presented

1. Introduction

The shock waves and high temperature gases are the active factors for sympathetic detonation. Sympathetic detonation in the atmosphere has been studied, however there are few reports of the underwater sympathetic detonation. Using the underwater sympathetic detonation, it would be possible to initiate simultaneously a relatively wide explosive in the water. The application of underwater sympathetic detonation to material and mechanical processing was investigated. An investigation of the basic characteristics of underwater sympathetic detonation of high explosive was conducted.

2. Experimental study

2.1 Experimental method

In order to investigate the basic characteristics of the underwater sympathetic detonation, optical observations and pressure measurements were performed. The experimental set up of optical observation is illustrated in Figure1. The donor and receptor explosives were Comp.B (RDX: 64%,

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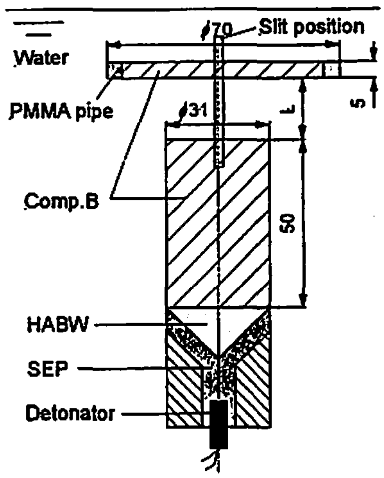


Fig. 1 Experimental set up for the optical observation.

TNT: 36%, detonation velocity: 7,900m/s, density: 1,700kg/m^3). The thickness of the donor was 50mm, and the diameter was 31mm. The diameter of receptor was 77mm, and the thickness was 5mm. The distance L between the donor and receptor explosives was changed in order to observe the underwater sympathetic detonation in the receptor explosive. The explosive lens, consisting of SEP and HABW explosives, was used to cause a planer detonation wave. The set up was placed in the water as shown in Figure 1.

The phenomenon in the experiments was recorded with a high-speed camera. The camera was an image converter camera (HADLAND PHOTONICS IMACON780), which can capture individual framing images and a streak image. The principle of the shadowgraph method was used in these images [1]. The framing images record an overall phenomenon at a selected interval of time. The streak record can capture a variation of a phenomenon on one axis. Therefore, it is often used to obtain data such as the velocity of underwater shock wave or detonation wave. The slit for streak photograph was set as shown in Figure 1. In these experiments, the streak velocity for the streak photograph was set to be 200ns/mm, and the interval time for the framing was 2μs.

In addition, measurements of the pressure of underwater sympathetic detonation were performed. Figure2 shows the set up for the measurement of pressure. The size of an explosive was the same as the one of the optical experiment. A manganin gage (KYOWA Electronic INSTRUMENTS CO. SKF-21725) [2] was placed under the receptor explosive for the measurement.

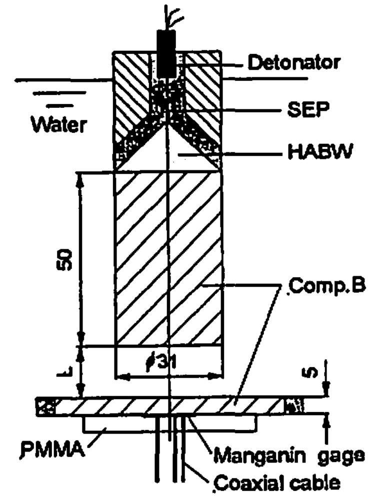


Fig. 2 Experimental set up for the measurement of pressure.

2.2 Experimental results

Figure3 shows the streak image in the case of (a) L=15. The luminous white line is the locus of detonation wave in the donor explosive. The shock waves, U_{s1} and U_{s2}, were generated from the surfaces of donor and receptor explosive respectively. It is difficult to judge the occurrence of underwater sympathetic detonation because a PMMA pipe was used for a protection of receptor explosive. Therefore, a judgment from the behavior of shock wave in water was made. Figure 4 shows

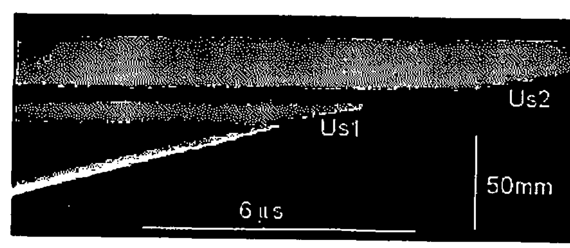


Fig. 3 Streak photographs by Shadowgraph method (L=15).

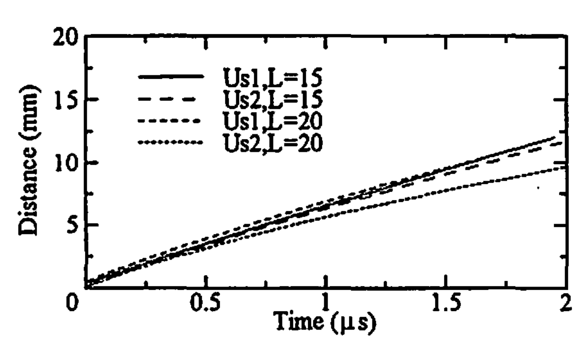
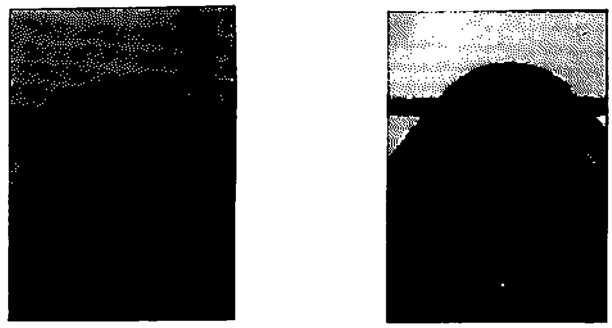


Fig. 4 Behaviors of shock wave in the water.



(a) L=15, Complete explosion (b) L=20, Incomplete explosion

Fig. 5 Framing photographs by Shadowgraph method.

the behavior of shock waves of U_{s1} and U_{s2}. In the case of (a) L=15, the slope of U_{s1} is almost same of the one of U_{s2}. However, in the case of (b) L=20, the slope of U_{s2} is smaller than the one of U_{s1}. It was shown that the shock wave velocity was slower than other shock wave.

The framing images are shown in Figure5. In the case of (a) L=15, the self-luminous of detonation wave occurred at the bottom of the receptor explosive, the underwater shock waves also occurred from the upper and lower surfaces of the receptor explosive. It could be recognized that the receptor explosive was detonated completely by the shock waves in water. On the other hand, it was not observed in the shockwave from the lower surface in the case of (B) L=20. Therefore it could be considered that the underwater shock wave only traveled through the receptor explosive or that the detonation of the receptor explosive was incomplete.

The results of pressure measurement for the receptor explosive are shown in Figure6. In the case of (a) L=15, the maximum pressure value was 27.7GPa, the value was almost the same as the C-J pressure of Comp.B. In the case of (B) L=20, the maximum pressure was 25.2GPa. It was considered that the maximum pressure of (B) L=20 was too high if the detonation did not occur.

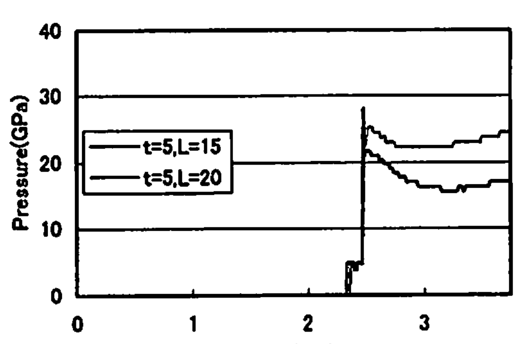


Fig. 6 Pressure histories of output data obtained by manganin gage method in underwater sympathetic detonation.

From the above experimental results, it could be concluded that the receptor explosive in the case of L=15 detonated, and it would be expected that the detonation condition of receptor explosive in the L=20 detonated incompletely rather than that it did not detonate,

3. Numerical study

3.1 Numerical simulation method

A numerical simulation of the underwater sympathetic detonation of Comp.B was performed. The effect of distance of water between the donor and receptor explosives for the ignition of receptor explosive was investigated. The numerical simulation model is illustrated in Figure 7. The size of explosives was the same as the experiments, allowing a comparison with the experiments. Because of symmetry, the model only shows a longitudinal section of the computational field. The sizes of the grids in the computational field are 0.5 mm by 0.5 mm for the calculation field. The properties of Comp.B used in the numerical

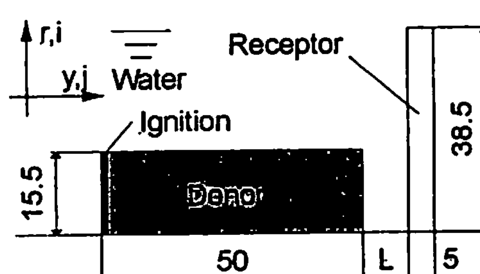


Fig. 7 Numerical simulation model for the underwater sympathetic detonation.

simulation were density: 1712kg/m^3, C-J detonation velocity: 7,980m/s, C-J detonation pressure: 29.5GPa.

The simulation method was the finite difference method (FDM) using Lagrangian coordinates[3]. The basic equations for the numerical calculation are those of mass, momentum and energy conservation in rectangular coordinates. The equations are

$$\frac{\partial \rho u}{\partial t}+\frac{1}{r}\frac{\partial \rho u}{\partial r}+\frac{\partial \rho v}{\partial z}=0 \quad (1)$$

$$\frac{\partial \rho u}{\partial t}+\frac{1}{r}\frac{\partial \rho u^2}{\partial r}+\frac{\partial \rho uv}{\partial z}=-\frac{\partial(P+q)}{\partial z} \quad (2)$$

$$\frac{\partial \rho u}{\partial t}+\frac{1}{r}\frac{\partial \rho uv}{\partial r}+\frac{\partial \rho v^2}{\partial z}=-\frac{\partial(P+q)}{\partial z} \quad (3)$$

$$\frac{\partial \rho e}{\partial t}+\frac{1}{r}\frac{\partial \rho uev}{\partial r}+\frac{\partial \rho ev}{\partial z}=-\nabla\cdot U(P+q) \quad (4)$$

where u, v are x-, y-directional velocity components, ρ, P, q, e indicate density, pressure, artificial viscous pressure and specific internal energy, respectively, ∇·U is the velocity divergence.

$$\nabla\cdot U=\frac{1}{r}\frac{\partial ru}{\partial r}+\frac{\partial v}{\partial z} \quad (5)$$

The above equations were used under cylindrical coordinate system together with the burn techniques and the equation of state for explosive and water. The burn technique calculates the reaction rate of explosive. Many researchers have proposed many techniques. In this work the Lee-Tarver model[4] was used because the burn technique incorporates the ignition and growth concept of shock initiation for high explosive.

The calculation of reaction rate of explosive that used L-T model is

$$\frac{d\lambda}{dt}=I(1-\lambda)^x\eta^r+G(1-\lambda)^x\lambda^y P^z \quad (6)$$

$$\eta=V_0/V_1-1 \quad (7)$$

where λ is the reaction rate of explosive that has reacted, t is time, V_0 is the initial specific volume of the explosive, V_1 is the specific volume of the shocked, unreacted explosive, P is pressure, and I, G, Z, x, y, and r are constants. The constants are I=44 (μsec^{-1}), G= 414 (Mbar^{-z} μsec^{-1}), Z=2.0, x=2/9, y=2/3, r=4 for Comp.B.

After the reaction rate l was calculated, the condition of reaction area was calculated by the reaction rate. The method used the two equations of state for mixtures of an unreacted explosive and a reacted explosive. The specific volume and the specific energy are V and E respectively, and an unreacted condition and a reacted condition are subscript s and g respectively. V and E is shown as the following,

$$V=\lambda V_g+(1-\lambda)V_s \quad (8)$$

$$E=\lambda E_g+(1-\lambda)E_s \quad (9)$$

The pressure was calculated by the Newton-Raphson method so that an equation of pressure balance, $P=P_g=P_s$, or an equation of temperature balance, $T=T_g=T_s$, was satisfied. The JWL (Jones-Wilkins-Lee) equation of state for the reacted explosive was used [5], and hugoniot date was used to fit the equation of state for the unreacted explosive Comp.B.

The JWL equation of state is shown as the following,

$$P=A\left[1-\frac{\omega}{VR_1}\right]\exp(-R_1\psi)+B\left[1-\frac{\omega}{VR_2}\right]\exp(-R_2\psi)+\frac{\omega E}{V} \quad (10)$$

where $y=V_1/V_0$, A, B, R_1, R_2, w are JWL parameter, the parameter for Comp.B is shown in Table 1.

Table 1 JWL parameters for Comp.B.

	A (Mbar)	B (Mbar)	R_1	R_2	ω
Reacted	5.242	0.07678	4.2	1.1	0.34
Unreacted	778.10	-0.05031	11.3	1.3	0.8938

The pressure calculation of water is calculated Mie-Grüneisen equation of state[6].

$$P=\frac{\rho_0 c_0^2\zeta}{(1-s\eta)^2}\left[1-\frac{\Gamma_0\zeta}{2}\right]+\Gamma_0\rho_0 E \quad (11)$$

where, $\zeta=1-V/V_0$, c_0, s are material constants, and G_0 is Grüneisen parameter. Table 2 shows the material parameters for water.

Table 2 Mie-Grüneisen Parameters for Water.

ρ_0(kg/m^3)	C_0 (m/s)	s	Γ_0
1000	1490	1.79	1.65

3.2 Numerical simulation results

Figure.8 shows the calculated pressure histories in the receptor explosive in both cases (L=15, L=20). The observation points along the central axis were set on an interval 1mm from the surface of the explosive, where the surface was 0mm. When the shock wave of water from the donor explosive was

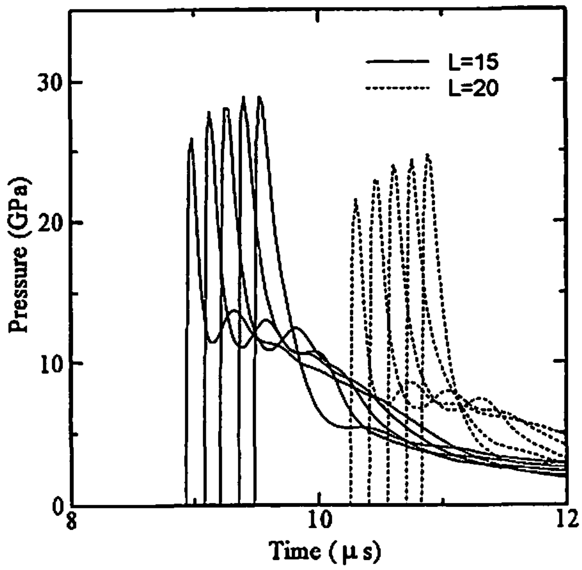


Fig. 8 Calculated pressure histories in the receptor explosive The observation points are 0, 1, 2, 3 and 4mm from the surface of receptor explosive.

incident to the receptor explosive, the ignition of explosive initiated. The incident pressure for the receptor explosive was attenuated in proportion to the distance of the water between the donor explosive and the receptor explosive. The incident pressure for the receptor explosives of L=15 and L=20 were 19.4GPa and 12.6GPa respectively.

The experimental pressure measurement and the calculated pressure values at the observation point 4mm show good agreement in both cases.

It was found that the pressure in the receptor explosive increased when the shock wave passed the observation points in both cases, and the reaction rate λ of all observation points were changed λ=1 (i.e., complete detonation) in several calculation routines. Hence, it could be concluded that the ignition of explosive had occurred in both cases. It was considered that the difference in the pressure value of L=15 and L=20 was caused by the difference of growth detonation that was generated by the difference of incidence pressure. The receptor explosive had detonated incompletely, and the condition of detonation was during the growth process. The growth of detonation was interrupted because the thickness of receptor explosive was only 5mm, since it was expected that measured pressure in the experiment was lower than C-J pressure.

4. Conclusions

The underwater sympathetic detonation of Comp.B was investigated. In the experimental study, a high-speed camera and a manganin gauge were used. The behaviors of both the detonation wave in the donor explosive and the shock wave of water were recorded by the streak image. The results of the streak record show the difference of the velocity of shock waves from the upper surface of receptor explosive in the both cases. However, no conclusion whether the receptor explosive detonated or not could be made. From observations using framing images, it was found that the explosive occur the self-luminous of detonation wave the explosive detonated in the case of L= 15. From the experiments using the manganin gauge, the maximum pressure on the surface of the receptor explosive of L=15 and L=20 were 27.7GPa and 25.2GPa respectively. We concluded the maximum pressure of L=20 was too high if the detonation had not occurred. The numerical simulation was performed to investigate the phenomenon. The numerical simulation was carried out by the finite difference method (FDM) using Lagrangian coordinates. The reaction rate of explosive was calculated by the method of Lee - Tarver model. The calculated pressure values agreed well with the experimental values. The pressure in the receptor explosive increased when the shock wave passed the observation points in the both cases, and the reaction rate λ of all observation points were changed λ=1 (complete detonation) in several calculation routines. In both case, the ignition of the explosive had occurred. However the receptor explosive detonated incompletely in the case of L=20, it was during the growth process. The growth of detonation was interrupted because the thickness of receptor explosive was only 5mm, since it was expected that measured pressure in the experiment measure was lower than C-J pressure.

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