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Visualization and Numerical Analysis of Stress Waves in Blasting Process

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Abstract : Visualization studies were performed both experimentally and theoretically to observe stress wave propagation in a material and its interaction with the free surface of the material in a blasting process. PMMA (polymethyl-methacrylate) plates were used as a transparent material. The stress wave was generated by initiation of an electric detonator. The stress waves in the PMMA specimen with the right-angled corner were observed by means of the shadowgraph system using a Q switched ruby laser as a light source. In addition to the experiment, a numerical analysis using smoothed particle hydrodynamics (SPH) was also carried out to clarify the dynamic behavior of stress waves in the blasting process. Transmittance and reflection of the stress wave at the free surface could be visualized by both the experiment and the numerical analysis.

Keywords : Explosives, Stress waves, Shadowgraphy, Smoothed particle hydrodynamics.

1. Introduction

Dynamics of stress waves, such as stress wave propagation in solid media, reflection and transmittance at the solid boundary, is one of the fundamental research problems which are related to interesting applications in blasting (Fourney et al., 1993). Especially, fracture control in blasting is very important in underground excavation and demolition of concrete structures. As pointed out by Fourney et al. (1978), ideal fracture control implies specification of the number of fracture planes, the initiation sites, the direction of fracture propagation and the stress field driving the fracture front. These requirements in fracture control are also important in partial demolition of concrete structures (Lauritzen, 1989). The blasting works must be done without damaging the remaining part of the structure. The conversion and transmission of explosive energy to the surroundings constitute a very complicated process. Therefore, it is necessary to examine the dynamic mechanism of stress waves, gases and cracks in the blasting process for achieving a high degree of fracture control.

On the one hand, numerical simulations are used to solve various nonlinear wave propagation problems with the progress of computers. Numerical simulations of the blasting process, such as an underwater detonation, were performed by several researchers (e.g., Molyneaux et al., 1994; Shin and Chisum, 1997). In most of these studies, a numerical method based on meshes for domain discretization was used. However, meshless methods have been developing to analyze a blasting process (Swegle and Attaway, 1995; Liu et al., 2001). Smoothed particle hydrodynamics (SPH) (e.g., Gingold and Monaghan, 1977), which was invented to solve astrophysical problems, is a meshless and Lagrangian method. This method is effective in a simulation of stress wave propagation problems in a material with free surfaces under large deformations in blasting.

In the present study, the model experiments using the PMMA specimens and the electric detonator as a charge were carried out to observe the stress wave in a blasting process by means of the laser-shadowgraph method. The dynamics of stress waves interacting with a right-angled corner in PMMA was analyzed. In addition to the experiment, a numerical analysis using SPH was also carried out to clarify the behavior of stress waves in a blasting process. Propagation of stress waves, reflection and transmittance at the interface between PMMA and air were visualized.

2. Experimental Procedure

The shadowgraph system using a ruby laser as a light source was set up. The Pokels cell Q switch with 20ns exposure time, two delay time generators, and a firing circuit to initiate the electric detonator were used to synchronize the emission of the pulsed laser beam with the blasting phenomena. These enabled us to get a giant pulse beam at a desired time and to obtain the high spatial and time resolved instantaneous visualization photographs. The optical arrangement of the shadowgraph system is shown in Fig. 1. This system consists of a set of concave schlieren mirrors of 150mm in diameter and 1500mm in focal length. The mirrors were used in an off-set arrangement. The shadowgraph image near the test section was recorded on the film by using the camera lens with the long focal length. A filter with high transmittance at the desired wave-lengths (693.5nm, band width 12nm) was placed in the front of the camera lens to prevent optical noises arising from the explosion of the detonator.

The PMMA plate of 20mm in thickness was used as a transparent material. The longitudinal elastic wave velocity of the PMMA plate is 2.62km/s. This value was obtained by the ultrasonic pulse method. PMMA has been shown by earlier workers to be a suitable material for laboratory model experiments on rock blasting (Field and Pedersen, 1971). The specimen geometry of PMMA is shown in Fig. 2. Dimensions are given in millimeters. The specimen was fabricated from a large sheet of PMMA (Acrylite S). The details of the experimental condition of the charge are schematically represented in Fig. 3. An electric detonator of 6.7mm in diameter and 45mm in length was used as a charge. The charge hole had the lower 10mm filled with the main charge, PETN 0.4g (penta-erythrito- ltetranitrate), of the electric detonator. The steel tube shown in Fig. 3 was used to prevent venting of the gaseous product and fragments generated by the explosion of the charge.

It is necessary to identify the initiation of the charge and the arrival of stress waves at the free surface of the specimen in order to analyze the dynamic behavior of the stress wave in blasting processes. In the experiment, the double pin ionization gauge was used to detect the initiation of the explosive charge. The piezoelectric gauge for detecting the pressure pulses of stress waves was attached to the free surface of the specimen as shown in Fig. 4. These signals were led to digital storage-type oscilloscopes. The diagram illustrating the experimental setup is shown in Fig.4.

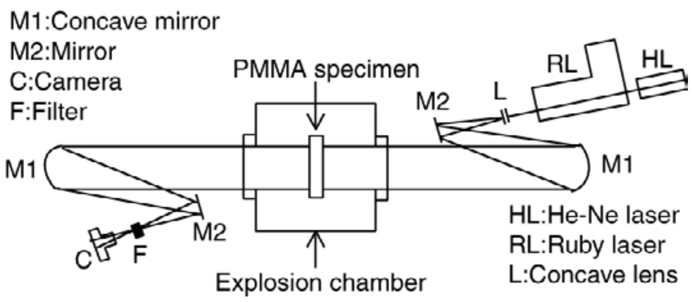


Fig. 1. Optical arrangement for shadowgraphy.

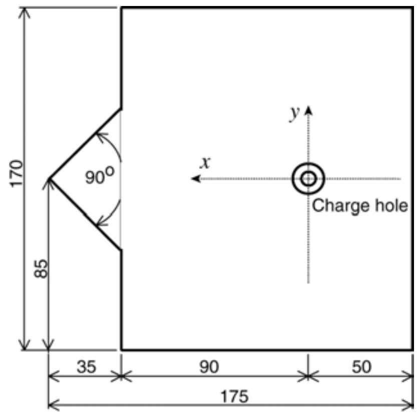


Fig. 2. Detail of PMMA specimen.

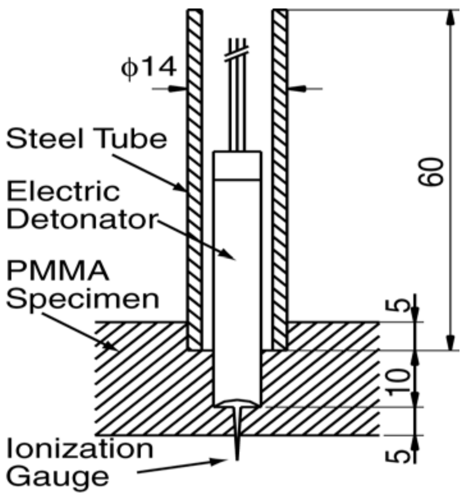


Fig. 3. Loading conditions of the explosive charge.

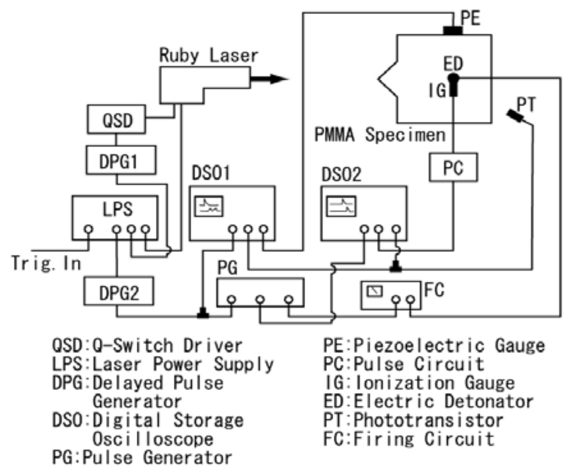


Fig. 4. Experimental setup.

3. Numerical Analysis Method

In the blasting process with high pressure and high-speed wave propagation, PMMA, air and explosive gas can be assumed to be inviscid and compressible. Thus Euler equations are used as governing equations,

$$\frac{D\rho}{Dt} = -\rho\nabla \cdot v, \quad \frac{Dv}{Dt} = -\frac{1}{\rho}\nabla p, \quad \frac{De}{Dt} = -\frac{p}{\rho}\nabla \cdot v, \quad p = p(\rho, e) \tag{1}$$

where ρ, v, e, p are the density, velocity vector, specific internal energy and the pressure, respectively. The last equation is an equation of state (EOS) for each medium. The EOS for ideal gas with the specific heat ratio, γ=1.4 is used for air.

$$p = (\gamma - 1)\rho e \tag{2}$$

Mie-Grüneisen equation is used for PMMA,

$$p = \frac{\rho_0 c_0^2 \mu}{(1 - s\mu)^2}\left\{1 - \frac{\Gamma_0 \mu}{2}\right\} + \Gamma_0 \rho_0 e \tag{3}$$

Table 1. Material parameters and coefficients in the EOS for PMMA.

Symbol	Meaning	Value
ρ_0	Initial density	1180kg/m^3
c_0	Sound speed	2260m/s
s	Grüneisen coefficient	1.82
Γ_0	Grüneisen coefficient	0.75

Table 2. Material parameters and coefficients in the EOS for SEP.

Symbol	Meaning	Value
ρ_0	Initial density	1310kg/m^3
D	Detonation velocity	6970m/s
P_{CJ}	C-J pressure	15.9GPa
e_0	Initial energy	2.16MJ/kg
A	Fitting coefficient	365GPa
B	Fitting coefficient	2.31GPa
R_1	Fitting coefficient	4.30
R_2	Fitting coefficient	1.00
ω	Fitting coefficient	0.28

where $\mu = 1 - \rho_0/\rho$. Parameters in Eq.(3) are listed in Table1. For explosive gas, the standard Jones-Wilkins-Lee (JWL) equation is employed,

$$p = A\left(1-\frac{\omega\eta}{R_1}\right)\exp(-R_1/\eta) + B\left(1-\frac{\omega\eta}{R_2}\right)\exp(-R_2/\eta) + \omega\eta\rho_0 e \tag{4}$$

where $\eta = \rho/\rho_0$. In this simulation, a SEP explosive is assumed to be a charge instead of PETN. Parameters in Eq.(4) are listed in Table2.

In SPH, a value of a function f (density, velocity etc.) and its gradient are expressed as a summation using a kernel function W with a smoothing length h,

$$< f_i >= \sum_{j=1}^{N} \frac{m_j}{\rho_j} f_j W(r_i - r_j, h), \qquad < \nabla f_i >= \sum_{j=1}^{N} \frac{m_j}{\rho_j} f_j \nabla_i W(r_i - r_j, h) \tag{5}$$

where m_j, r_j are the mass and position vector of the particle j, ∇_i means to take the gradient with respect to the particle i, N is the total number of particles that have effects on the particle i. The two-dimensional cubic spline function is used as the kernel function,

$$W(S,h) = \frac{15}{7\pi h^2}\begin{cases} 2/3 - S^2 + S^3/2, & 0 \le S < 1 \\ (2-S)^3/6, & 1 \le S < 2 \\ 0, & S \ge 2 \end{cases} \tag{6}$$

where $S = |r - r'| / h$. The smoothing length h is obtained from the following equation in each calculation step,

$$h_i^{n+1} = \frac{1}{2} h_i^n \left[1 + \left(N_s / N_i^n \right)^{1/2} \right] \tag{7}$$

where N_s is the value of N on initial condition. A hierarchy tree search method is adopted to determine N as the nearest neighbor searching method (Hernquist and Kaz, 1989).

In standard SPH, the symmetrized form of the pressure gradient is obtained as follows.

$$\frac{1}{\rho} \nabla p = \nabla \left(\frac{P}{\rho} \right) + \frac{P}{\rho^2} \nabla \rho \tag{8}$$

However, this expression isn't suitable in this study, because an abrupt change of the density exists at the boundary between PMMA and air. Then, we used the expression as follows.

$$\frac{1}{\rho} \nabla p = \frac{\nabla P}{\rho} + \frac{P}{\rho} \nabla 1 \tag{9}$$

Using Eq.(9), the following discretized forms of SPH are obtained,

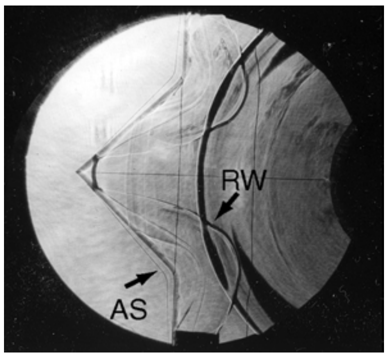
$$\begin{cases} \dfrac{D\rho_i}{Dt} = \displaystyle\sum_{j=1}^{N} m_j (v_i - v_j) \cdot \nabla_i W_{ij} \\ \dfrac{Dv_i}{Dt} = -\displaystyle\sum_{j=1}^{N} m_j \left(\frac{p_i + p_j}{\rho_i \rho_j} + \Pi_{ij} \right) \nabla_i W_{ij} \\ \dfrac{De_i}{Dt} = \dfrac{1}{2} \displaystyle\sum_{j=1}^{N} m_j \left(\frac{p_i + p_j}{\rho_i \rho_j} + \Pi_{ij} \right) (v_i - v_j) \cdot \nabla_i W_{ij} \\ \dfrac{Dr_i}{Dt} = v_i \end{cases} \tag{10}$$

where $W_{ij} = W(r_i - r_j, h)$, Π_{ij} is the artificial viscosity (e.g., Monaghan and Gingold, 1983, Monaghan, 1988). The artificial viscosity is used to prevent particle penetrations and capture shock waves. These equations can be calculated by the numerical time integration method such as leapfrog, predictor-corrector and Runge-Kutta schemes. Leapfrog method is used for its low memory storage and efficiency.

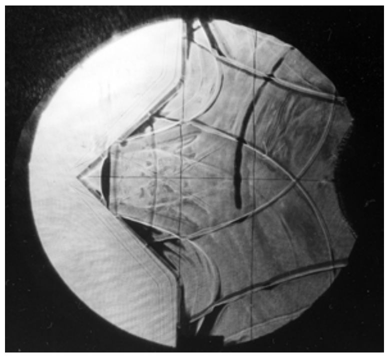
In this study, the two dimensional and axisymmetrical simulation is carried out in order to simplify the problem. The calculating domain is from –100 to 175mm on x axis and from 0 to 135mm on y axis. Initial particles are distributed over the calculating domain with 1mm space. About 40,000 particles are used in the simulation, about 14,500 particles are included in PMMA, most of rests are in air and a few particles are in explosive gas. PMMA and air are initially at an atmospheric condition. The initial condition of explosive gas is given by the assumption that the density and energy of the gas are equal to those of the explosive charge. Most exterior air particles are fixed at atmospheric condition owing to no influence of the stress wave. The time increment of leapfrog method is set at 0.05μs.

4. Results and Discussion

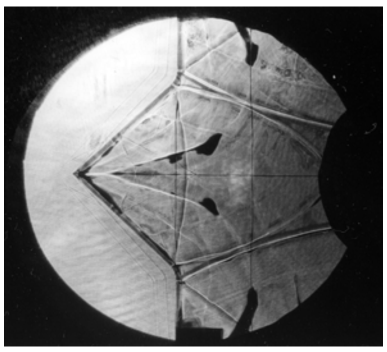
Figure 5 shows the shadowgraphs of the incident stress waves interacting with the right-angled corner of the PMMA specimen. As shown in the previous experiment on stress wave propagation in PMMA (Nakamura, 1996), several incident stress waves are visible in these shadowgraphs, The secondary wave is not the reflected wave from the free surface near the charge hole. The stress waves propagate through the PMMA specimen and interact with the free surface of the specimen. The propagation time of the first incident stress wave in the PMMA specimen from the charge hole to the free surface at the distances of 85mm was about 26.5μs. The propagation time can be evaluated from the piezoelectric gauge data and the ionization gauge data. The mean velocity of the stress wave was about 3.2km/s. This value is greater than the longitudinal elastic wave velocity of PMMA. The result is in good agreement with that of the previous experiment. The shock impedance of air is very low compared with that of PMMA. Therefore, reflected rarefaction waves (RW) at the free surface of the PMMA specimen and shock waves (AS) in air near the right-angled corner of the specimen are generated in Fig. 5. The shock waves in air are initiated by displacement of the free surface of the specimen. As shown in Fig. 5(c), an interference of the reflected rarefaction waves appears on the bisector of the right-angled corner, and the beginning point of the interference is the apex of the right-angled corner. In addition to these behaviors, the shadow spot appears near the apex of the right-angled corner. This shadow spot is caused by the tensile deformation of the specimen.



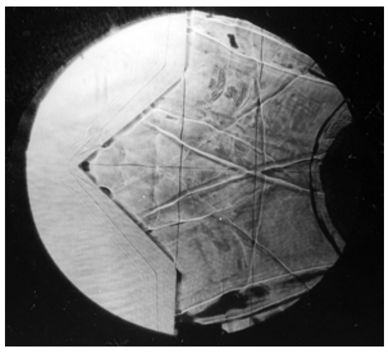
(a) t=36μs



(b) t=48μs



(c) t=52μs



(d) t=61μs

Fig. 5. Shadowgraphs of the stress waves interacting with the right-angled corner in the PMMA specimen. Each photograph is of a different experiment. Time t after the explosion of the charge is indicated.

Figures 6 and 7 show the density distributions obtained from the simulation using SPH. It is difficult to show the density of PMMA together with that of air, because the density of air is very small compared with that of PMMA. Therefore, we use the density range of 1180-1183kg/m^3 in Fig. 6 and that of 1.2-2.0kg/m^3 in Fig. 7, respectively. The velocity of the incident stress wave obtained from the simulation is smaller than that of the present experiment. The explosive gas in the charge hole expands onto a horizontal plane in the simulation. This behavior is different from that of the gaseous product generated by the explosion of the charge in the experiment. This difference affects the velocity of the incident stress wave. It can be also considered for the PMMA specimen that the equidistant longitudinal elastic waves are generated by repeated wave reflections on the side walls of the specimen. Then, it hardly seems to be treated as a two-dimensional problem for this experiment. In Fig. 6(a), (b), air particles near the wedge-shaped free surface are moved by the interference of the incident stress wave. As a result, the density near the wedge-shaped free surface becomes high and the air shock wave is generated as shown in Fig. 7(a), (b). In Fig. 6(c), (d), the expansion of the density in PMMA after reflection of the incident wave starts near the wedge-shaped corner. The same distributions are obtained about the pressure.

Figure 8 shows the distribution of the second derivative (Brookshaw, 1994) of the density, i.e. shadowgraph. The incident stress wave (ISW) is shown in Fig. 8(a), (b). The shock wave in air (AS) generated by the interference of the incident stress wave is also shown in Fig. 8(b), (c), (d). The behavior of the incident stress wave and the air shock wave are similar to that of the experiment shown in Fig. 5, qualitatively. However, the reflected rarefaction wave and its interference in PMMA can't be appeared clearly both in the numerical shadowgraph and in the density contour map.

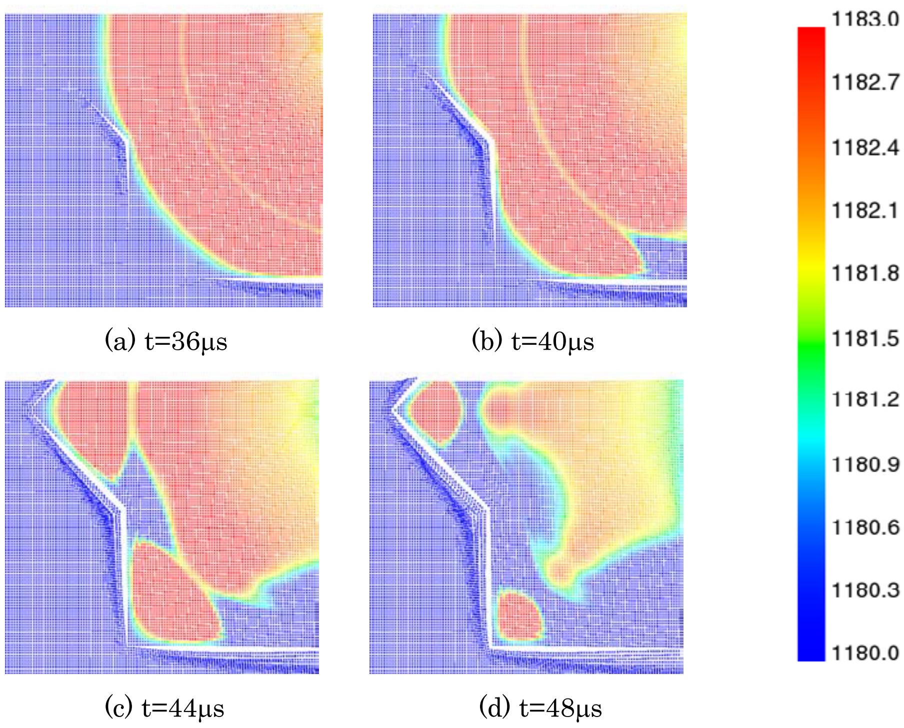


Fig. 6. Density distributions within the range from 1180kg/m^3 to 1183kg/m^3.

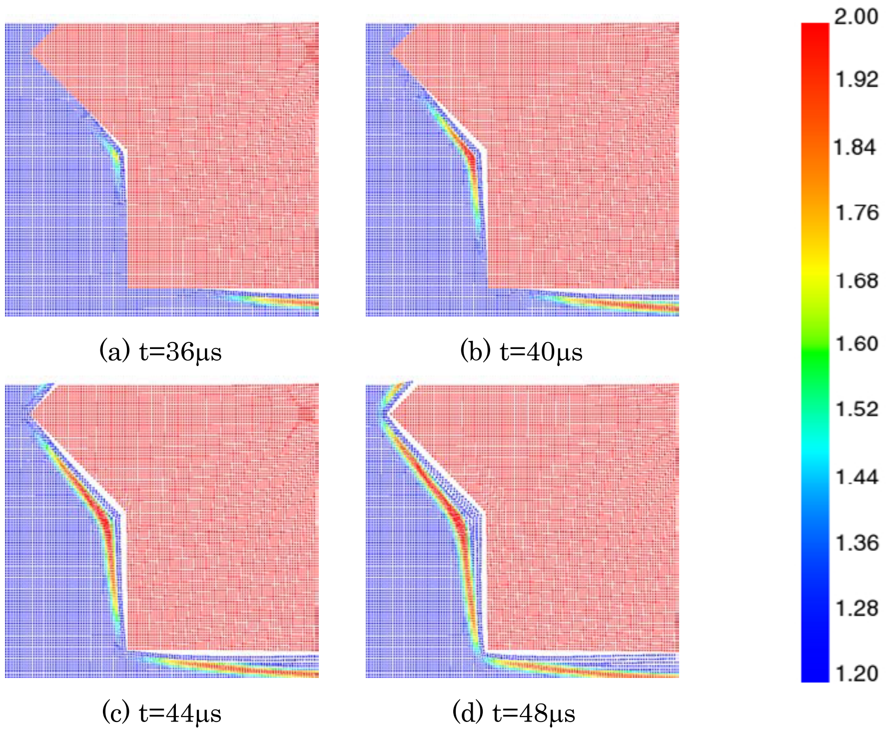


Fig. 7. Density distributions within the range from 1.2kg/m^3 to 2.0kg/m^3.

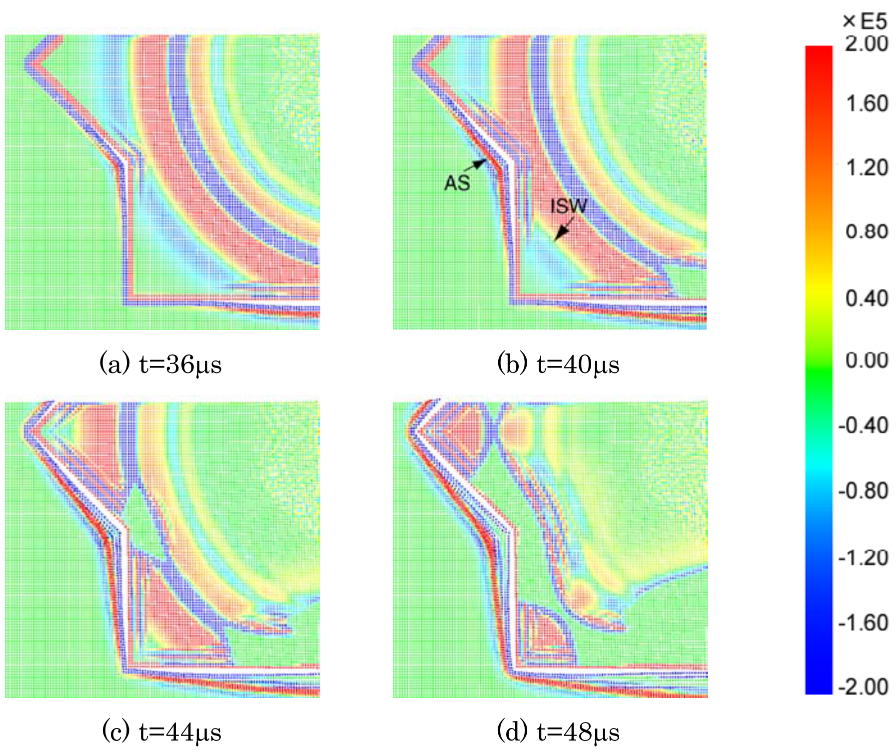


Fig. 8. Second derivative of density distributions.

5. Conclusion

The objective of this study is to examine the stress wave propagation and its interaction with the solid boundary in blasting processes. The flow visualization test using the shadowgraph system with the Q switched ruby laser and the numerical analysis using SPH were carried out to clarify the behavior of stress waves interacting with the right-angled corner of the PMMA specimen in the blasting process. The shadowgraphs showed the several incident stress waves initiated from the charge hole, the reflection and transmittance process of the stress waves at the free surface of the specimen. The shock waves in air generated by the outgoing movement of the free surface were also indicated. The numerical simulation using SPH indicated similar behaviors of the incident stress wave and the air shock wave, qualitatively. However, the behavior of the reflected wave in PMMA could not be demonstrated clearly.

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