Numerical Simulation of Explosive Forming Using Detonating Fuse

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ABSTRACT
The explosive forming is a characteristic method. An underwater shock wave is generated by underwater explosion of an explosive. A metal plate is affected high strain rate by the shock loading and is formed along a metal die. Although this method has the advantage of mirroring the shape of the die, a free forming was used in this paper. An expensive metal die is not necessary for this free forming. It is possible that a metal plate is formed with simple supporting parts. However, the forming shape depends on the shock pressure distribution act on the metal plate. This pressure distribution is able to change by the shape of explosive, a mass of explosive and a shape of pressure vessel.

On the other hand, we need the pressure vessel for food processing by the underwater shock wave. Therefore, we propose making the pressure vessel by this explosive forming. One design suggestion of pressure vessel made of stainless steel was considered. However, we cannot decide suitable conditions, the mass of the explosive and the distance between the explosive and the metal plate to make the pressure vessel. In order to decide these conditions, we have tried the numerical simulation on this explosive forming. The basic simulation method was ALE (Arbitrary Lagrangian-Eulerian) method including with Mie-Grüneisen EOS (equation of state), JWL EOS, Johnson-Cook constitutive equation for a material model. In this paper, the underwater pressure contours to clear the propagations of the underwater shock wave, forming processes and deformation velocity of the metal plate is shown and it will be discussed about those results.

1. INTRODUCTION

A food processing equipment using the underwater shock wave has been developing in Japan [1]. The processing mechanism is crushing with the spalling phenomenon of shock wave. The effect is extraction improving, softening, sterilizing etc. with non-heating. The pressure vessel for crushing for the processing of the variety foods has been designed and manufactured. We need a pressure vessel for food processing by underwater shock wave. Therefore, we propose making the pressure vessel by the explosive forming. Only a few of these pressure vessels will be made. One design suggestion of the pressure vessel made of

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stainless steel was considered. The pressure vessel is needed that the length, thickness and depth of it were 400mm, 8mm and 100mm, respectively. It is possible that a metal plate is formed with simple supporting parts. However, the forming shape is depending on the shock pressure distribution acting on the metal plate. This pressure distribution is able to change by the shape of explosive, mass of explosive and the shape of pressure vessel. The numerical simulation was carried out. Two kinds of numerical simulation models are considered. One is a model to compare with pressure profile by an experiment. Another is the explosive forming model. The explosive was detonation fuse (is described as 'DF'). The distance between DF and the stainless-steel plate was 50mm. We know the special quality about the explosion of DF. An equation of state of the pressure and the specific volume which can often indicate its special quality is used. The equation of state (is described as EOS) was JWL (Jones-Wilkins-Lee) EOS [2]. All models were calculated as plane strain and symmetrically. Basement of simulation method was ALE (Arbitrary Lagrangian-Eulerian) method [3], because on the numerical simulation is able to solve the interaction between liquid and structure. Mie-Grüneisen EOS [4] was used as the equation of state which can solve the shock properties of water. Because the metal plate is involved high strain rate, Johnson-Cook Equation as material model [5] included the effect of strain rate was applied in this simulation.

2. PRESSURE VESSEL FOR FOOD PROCESSING

The development of food processing system using the underwater shock wave has been progressing. The underwater shock wave is generated by high-voltage underwater discharge during the electrode. When the underwater shock wave acts on the food, various effects were occurred. This equipment has been developing and it can be possible continuously processing, as shown in Figure 1. The pressure vessel is used in this equipment. In this paper, we propose making of the pressure vessel by the explosive forming. Figure 2 is a schematic diagram of the explosive forming to make the pressure vessel. The material is a stainless-steel plate has width-430mm, length-600mm and thickness-8mm. 750mm length DF is set at central over the stainless steel and in the underwater. Above of the stainless steel is a container by two side walls made of steel and PMMA (Polymethyl-methacrylate) plate. The container is filled water. Before this processing, we have tried the numerical simulation for confirm the deformation shape and bulge depth of stainless steel.

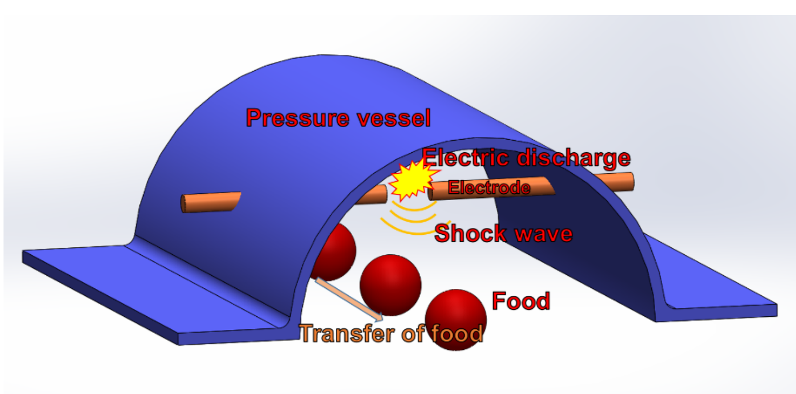


Figure 1 Schematic diagram of food processing.

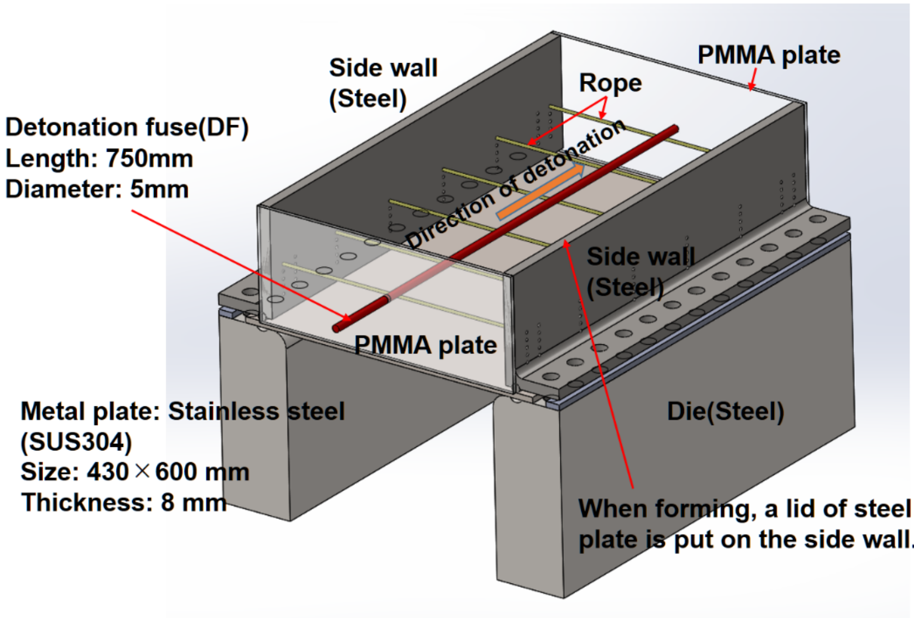


Figure 2 Set up diagram of the explosive forming.

3. NUMERICAL SIMULATION

Two numerical simulation models are shown in Figure 3. All models were calculated as plane strain and symmetrically. One is a model to compare with pressure profile by experiment. In order to clear the appropriateness of this simulation method, the measurement result of pressure profile in past research and this simulation result are compared. The distance between DF and the pressure pick up sensor was 50mm. DF and water region were calculated as only Eulerian elements. Top, the right side and the bottom of water assumed as free flow surface.

Another (b) is the explosive forming model. In this model, four DFs are set the underwater and outer is the closed pressure vessel made of tool steel. The distance between DF and the stainless steel is 50mm. The metal die also assumed as made of tool steel. The pressure of DF and water were calculated by JWL EOS and Mie- Grüneisen EOS, respectively. The relationship of the stress and strain of stainless steel and tool steel were calculated by Johnson-Cook constitutive equation. In this model was calculated by ALE method. The water region was Eulerian elements and other metal parts were Lagrangian elements. All numerical simulations were computed by RADIOSS, Altair Engineering, Inc.

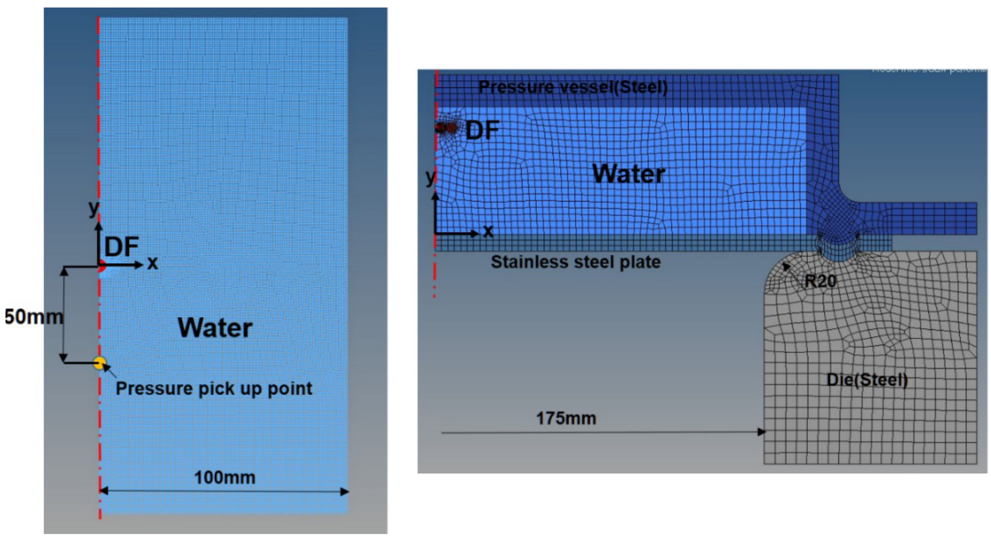
The pressure, P in detonation products of explosive DF was calculated by using the JWL EOS [2]. JWL EOS is expressed in the following equation (1),

$$P = A\left[1-\frac{\omega}{VR_1}\right]\exp(-R_1V) + B\left[1-\frac{\omega}{VR_2}\right]\exp(-R_2V) + \frac{\omega e\rho_0}{V} \qquad (1)$$

where, A, B, R1, R2, C and ω are JWL parameters. V is the ratio of the volume of the product gases to initial volume of the undetonated explosive. For the explosive DF, those constants were obtained from cylindrical expansion test and are given in Table 1.

Table: 1 The JWL parameters for DF.

ρ_0(kg/m^3)	A (GPa)	B (GPa)	R1	R2	ω
1200	452.35	8.85	5.49	1.43	0.28



(a) DF and water model for comparison with experimental data.

(b) Explosive forming model.

Figure 3 Simulation models of model(a) and (b).

The pressure of water was calculated by Mie-Grüneisen EOS [4], is expressed in the following equation (2),

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

where, ρ_0 is initial density. e is internal energy, Γ_0 is Grüneisen parameter, $\eta = 1 - \rho_0 / \rho$, c_0 and s are material constants. The values of those constants are given in Table 2.

Table 2: Mie- Grüneisen EOS parameters for water.

ρ_0(kg/m^3)	c_0 (m/s)	s	Γ_0
1000	1490	1.79	1.65

As the constitutive equation of the stainless-steel plate (SUS304) and tool steel, simplified Johnson-Cook's equation was used. The equation is described in the following equation (3),

$$\sigma = \left(A + B\varepsilon^n\right)\left(1 + C \ln \varepsilon^*\right) \tag{3}$$

where, σ is the equivalent stress, ε is the equivalent strain and ε* is the equivalent strain rate. Then, A, B, C, and n are shown Table 3 [5].

Table 3: Johnson-Cook equation parameters.

Material	ρ_0(kg/m^3)	A (GPa)	B (GPa)	C	n
SUS304	7890	554	995	0.046	0.64
Tool steel	7750	1539	477	0.012	0.18

4. RESULTS AND DISCUSSIONS

Pressure contours of the simulation model (a) at 0 to 57.0 μs and pressure levels are shown in Figure 4. Higher pressure region, about 500 MPa are indicated in red color, then lower pressure region is in blue color. We can see that the underwater shock wave propagated in circular. The peak pressure is gradually attenuated from approximately 24μs. On this simulation, a pressure value of water element which is the place in 50mm distance from DF pick up. Then, the pressure profile was compared with the pressure measurement date on the experiment.

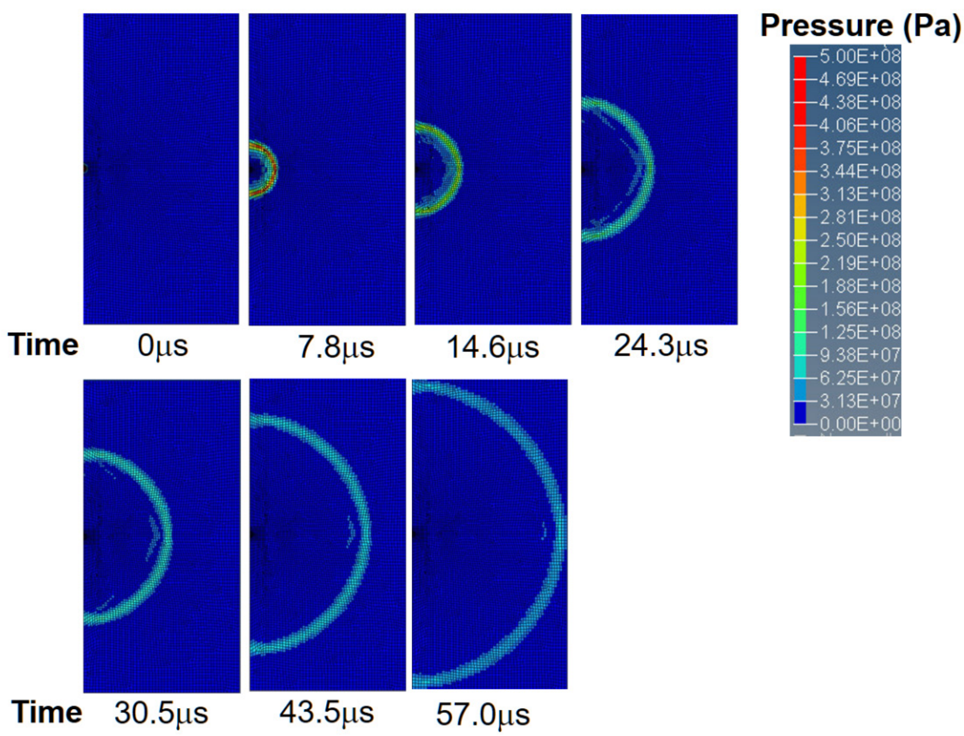


Figure 4 Pressure contours of model (a).

Figure 5 shows pressure profiles at horizontal every 10mm positions. In all pick up points, the vertical distance from DF was 50mm. The peak pressure value is gradually reduced with position goes away from center. Maximum peak pressure was approximately 180 MPa at the center.

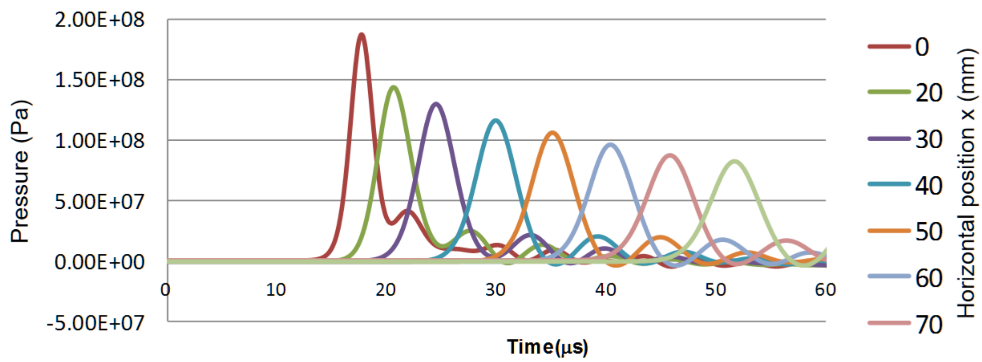


Figure 5 Pressure history at horizontal every 10mm positions from result of model(a).

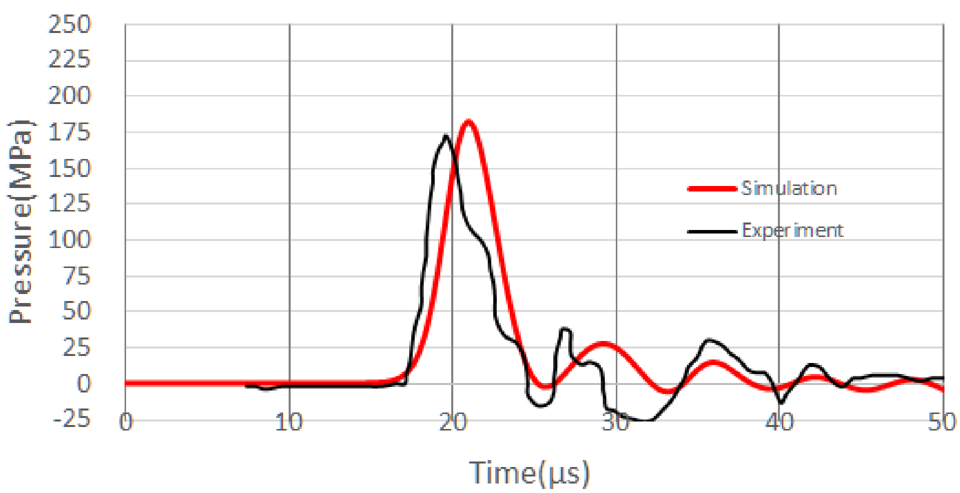


Figure 6 Pressure profiles compared with experimental data.

Experiments for measurement of the pressure value were carried out. The measurement device was a copper bar and strain gages which was pasted two points on the bar. The position of tip of the bar was distance of 50 mm from DF. These were set underwater. The underwater shock wave from the DF was propagated and it was hit and through in the bar. When the shock wave goes through in the bar, we could get two electric pulses by two strain gages. We could get the elastic wave velocity by time interval of two electric pulses and the distance of the position of two strain gages. The measurement pressure value was calculated by the product of this velocity, sound velocity and density of the cooper bar [6].

Figure 6 shows the pressure profile from simulation data compare with the pressure measurement data. Although the first peak pressure of both are small time difference, both peak pressure value almost agrees. The first peak pressure value is approximately 180 MPa. The result of model (b) at 4 to 1000 μs is shown in Figure 6. After detonation of DF, the underwater shock wave immediately propagated circular inside of the pressure vessel. The first shock pressure reaches to the top surface of stainless steel at 20μs. The central part of the

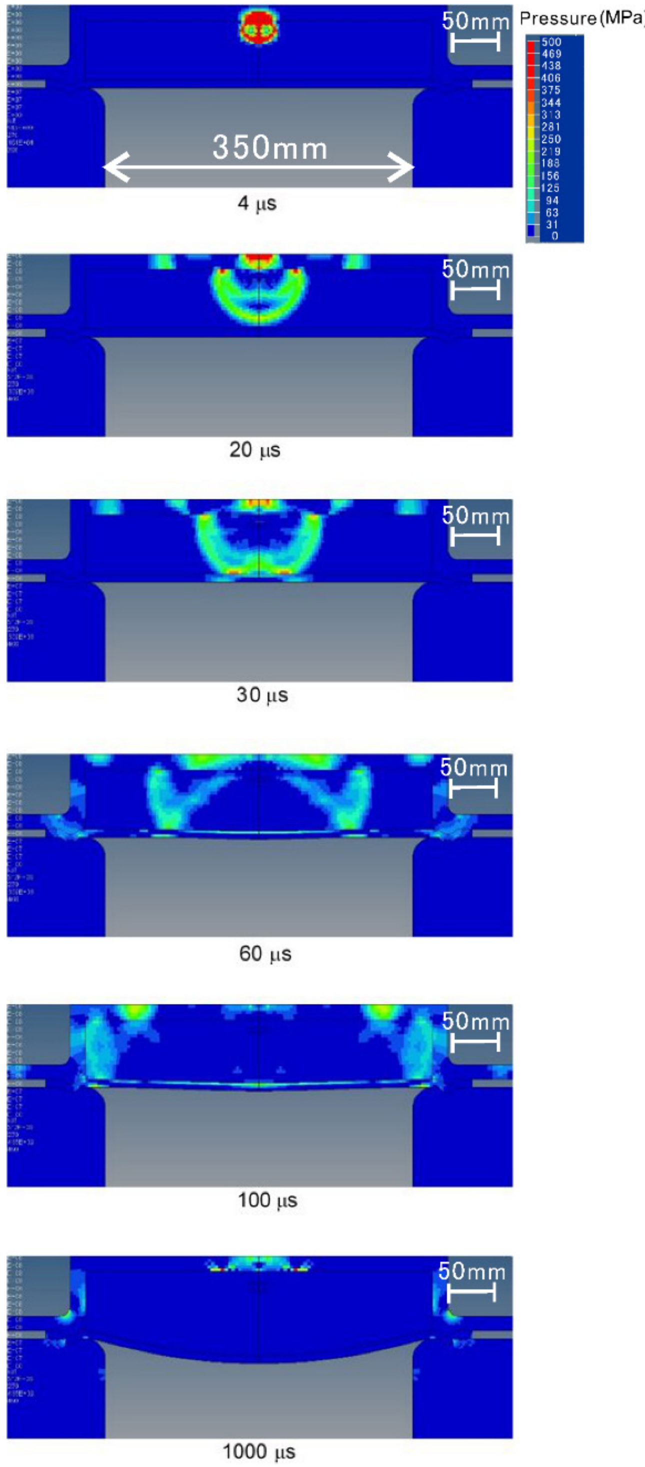


Figure 7 Pressure contours of model (b).

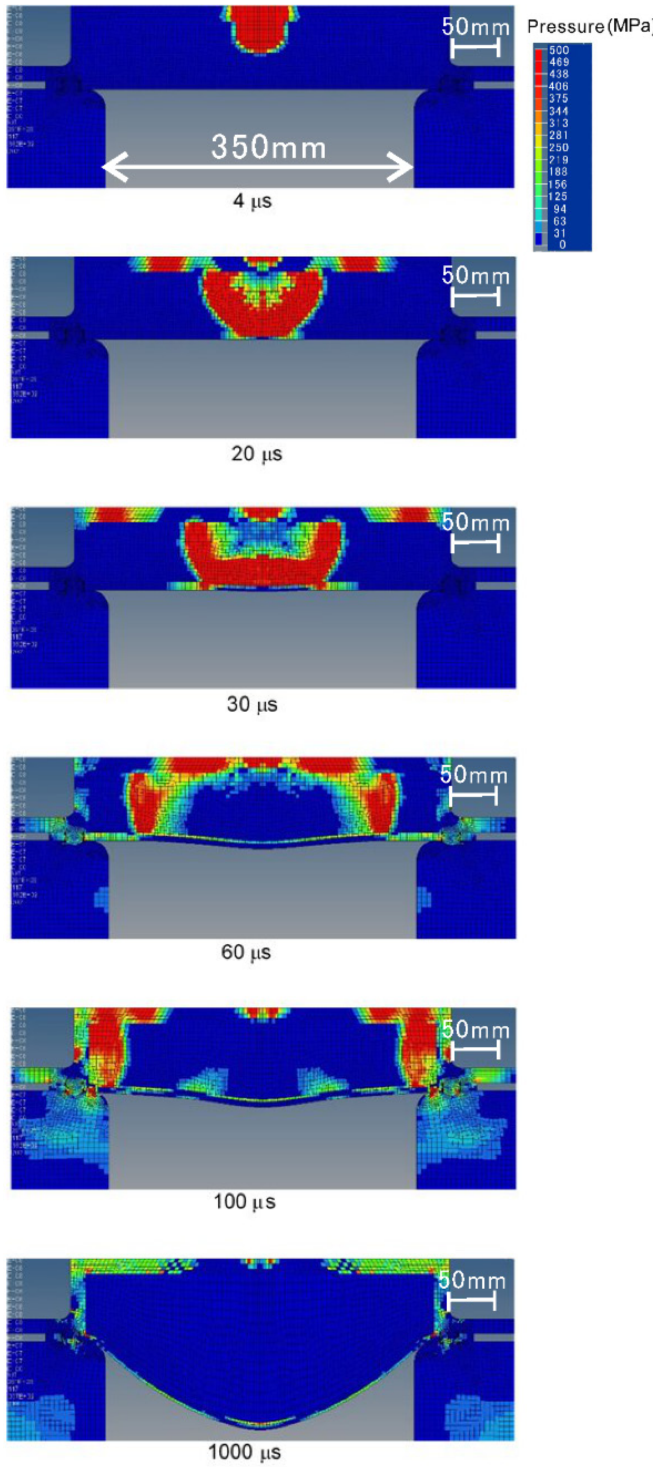


Figure 8 Pressure contours of model (c).

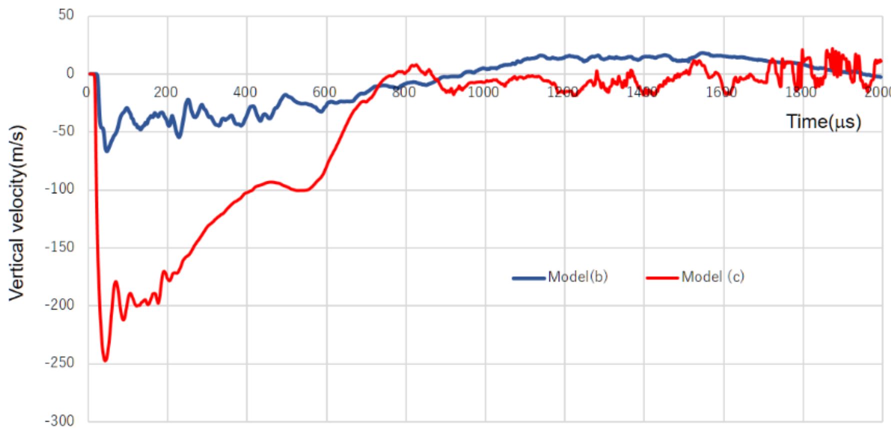


Figure 9 Vertical velocity at center of stainless steel.

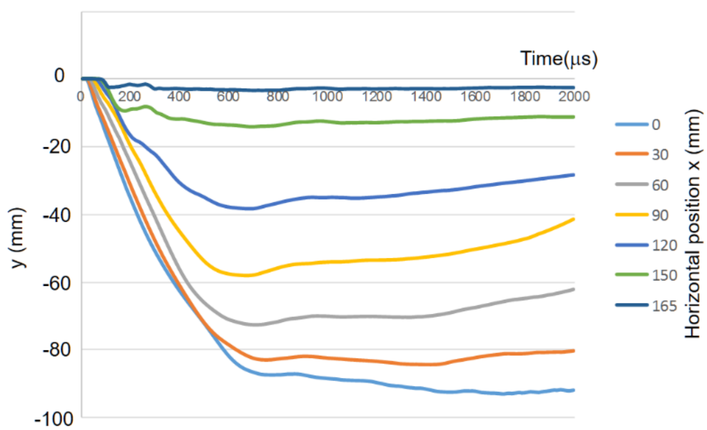


Figure 10 Vertical position profile to horizontal position in each 30mm intervals of model (c).

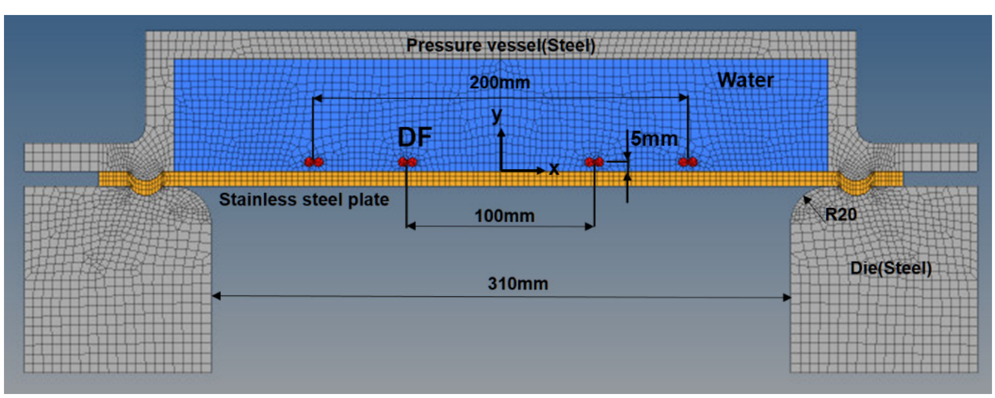


Figure 11 Simulation model (d) of 8DFs and close distance from stainless steel plate.

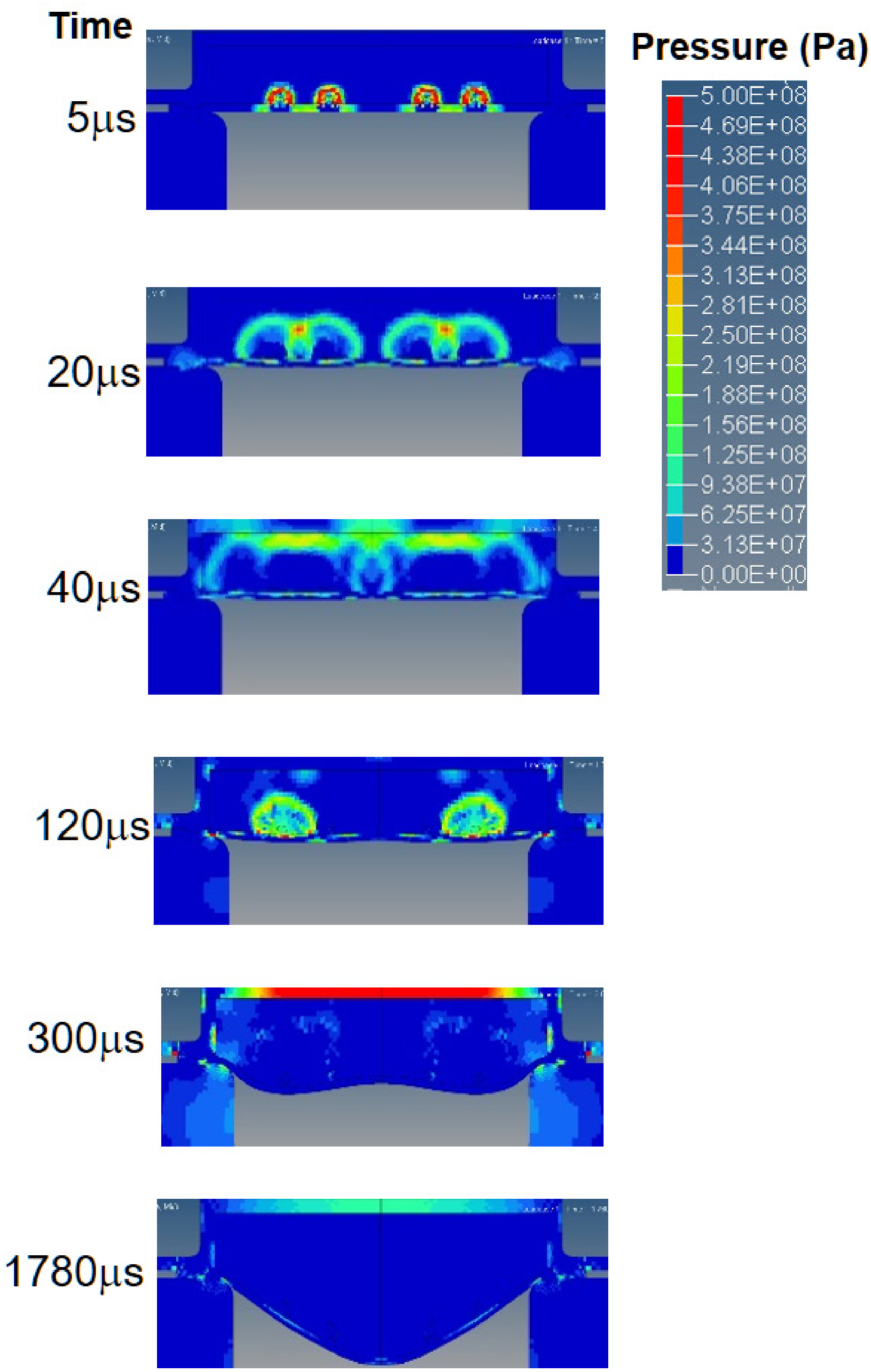


Figure 12 Pressure contour and deformation processes to final shape of model(d).

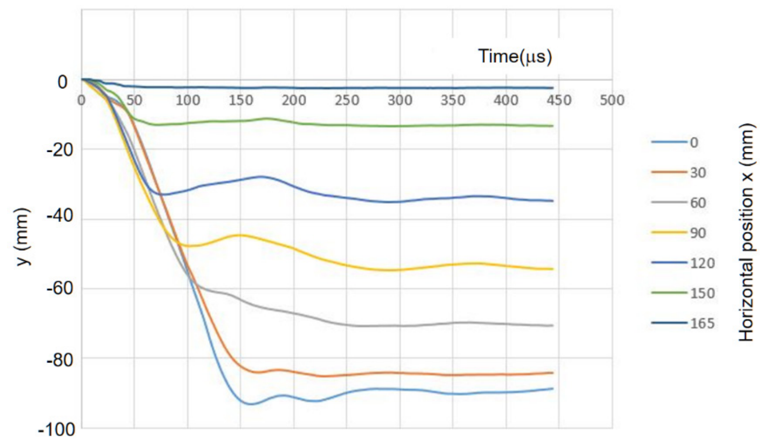


Figure 13 Vertical displacement profiles to horizontal position in each 30mm intervals of case(d).

stainless steel begins small form. The last deformation shape of the stainless-steel plate took on the roundness. However, the maximum deformation height (bulge depth) was approximately 10 mm. This value is not satisfied. We need more over than 100 mm bulge depth.

Therefore, we considered another model (c). The model (c) is similar with model (b) and it have more explosive mass. The explosive region was quadrilateral in height, 20mm and the width, 30 mm in the case of model(c). The pressure contours on the model(c) with same time intervals of Figure 7 is shown in Figure 8. Because the explosive region was larger than the model (b), the underwater shock wave reaches the stainless steel is earlier than the case of the model (b). The stainless-steel deformation begins from approximately 30 µs. At the first, the central part of the stainless steel was deformed, the reflected shock wave from the side wall of pressure vessel affected to the deformation of the plate near die corner. The final bulge depth in this case at 1000 µs was approximately 30 mm in three times of the case of model (b). The vertical velocity of central part of the stainless steel in both cases of model (b) and (c) were compared. The results are shown in Figure 9. Negative value is projected side of the center of stainless steel plate. In the case of model (b), maximum velocity was approximately 65 m/s. One of model(c) was reached more value, up to approximately 245 m/s. Figure 10 shows the vertical position profile to horizontal position in each 30mm intervals of model (c). The center part of the plate was projected and the maximum depth. Its value was approximately 94 mm.

Therefore, we considered and more model is shown in Figure 11, model(d). In this model, 8 DFs were used. These set at four places on each 2DFs. Then, DFs set positions were shown in that Figure. The distance between stainless steel plate and DF were very close.

Figure 12 shows the pressure contour and deformation processes to final shape of model(d). After DF was detonated, two points of stainless steel began to deform at first. Then, those two points, downward deformation makes upward deformation at center part, and this part was projected to downward.

Figure 13 shows vertical displacement profiles to horizontal position in each 30mm intervals of case(d). The center part of the stainless steel was projected and the maximum depth. Its value is approximately 93 mm.

5. CONCLUSIONS

In order to make a pressure vessel for food processing, we proposed using the explosive forming. Before making the pressure vessel, the forming method was checked by numerical simulations. The result of this research is concluded in the following,

- The result of the pressure profile agreed with the measured value by the experiment well.
- The peak pressure was approximately 180 MPa at 50mm distance from DF.
- In case of explosive forming simulation model(b), which used 4 DFs, we could not get enough deformed shape of stainless steel.
- Bulge depth of stainless steel was enough on more explosive mass, model (c) and model(d). In model(c), vertical velocity of center of stainless plate were more than 247 m/s and the maximum vertical displacements were more than 94 mm.

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