Article

The new trial of explosive forming

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In recent years, many studies for increased productivity of metal forming have been performed. In these fields, it is important to decrease production cost make lower. However, in general a very expensive metal die is necessary for metal forming. Consequently, it is difficult to decrease the cost by excluding the metal die. We have been developing a technique for metal forming without using the metal die as a novel method for lowering costs. We have considered the free forming by explosives using underwater shock wave generated by detonation of explosives placed in water. This technique uses only a metal die with circular edges, it does not use an expensive metal die with the same shape as the product. We investigated varying the pressure condition acted on the metal plate by changing the set position of the explosive. We have also been trying to establish metal pipe forming using an underwater shock wave. In this technique the cross section becomes a desired shape using the underwater shock wave by detonation of explosive in water.

In this paper, we present some experiments of these methods (free metal forming and metal pipe forming) and some simulation results by FDM (Finite Difference Method). This numerical simulation can express the detonation process of explosive, the propagation of the underwater shock wave and the deformation process of a metal plate or a pipe.

1. Introduction

Many small quantity batch type explosive forming productions have been increasing in correspondence to consumers' needs. Many formed metal parts of these manufacturing techniques are produced using very expensive metal dies and devices. The cost to produce these parts are very high, so a new method was proposed[1]. It was a method without a metal die for forming using underwater shock wave generated by the detonation of explosive, called free forming. The method is able to produce metal plate formed to optional shapes by changing the set up position of the explosive. In this method, because the set up position of explosive is changed, we can easily change the pressure distribution imparted to the metal plate.

Some experiments were conducted using the free forming by underwater shock waves. In these experiments, a circular pressure vessel was used and the explosive set up position was changed in its height from circular metal plate. We obtained some eccentric spherical shape of metal plate. From these experimental results, we present the effect of these conditions on the formed shape of the metal plate.

We have also done metal pipe forming using this method. We investigated different heights between the explosive and the top of metal pipe. The inside of the metal pipe was hollow or filled with some materials such as water, soil, air, and so on. Consequently, we can obtain various shapes of metal pipe. We did some experiments to estimate

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effects on the shape of the metal pipe by these conditions.

Numerical simulations of free metal sheet forming and simple axial symmetric modeling of metal pipe forming using FDM were also performed. The methods and results are presented in this paper.

2. Experimental study

2.1 Eccentric spherical free forming

Figure 1 shows the device for the experiments. The device was assembled from two parts, the upper part was the pressure vessel and the lower part was to hold the blank. A 1 mm thick circular copper plate was held between the two parts with fastening bolts. These devices were submerged, allowing the pressure vessel to be filled with water. The edge of the lower part has circular curvature and water could not flow under the blank. The lower part has an exhaust port to allow a vacuum via a vinyl hose. The explosive was SEP (detonation velocity: 6970m/s, detonation pressure: 15.9GPa, initial density: $1310kg/m^3$) provided by Asahi Kasei Corp. The set up position of this explosive was changed as Fig. 1, 'h' is height of the surface from the blank. We defined the x-y coordinate in Fig.1 to correspondence to experimental results. Table 1 is the set up condition of this experiment. As this table indicates, we considered five cases of set-up position of explosive. The horizontal position, x is distance from the left-sidewall. The measurement of the final deformed shape of the copper plate in

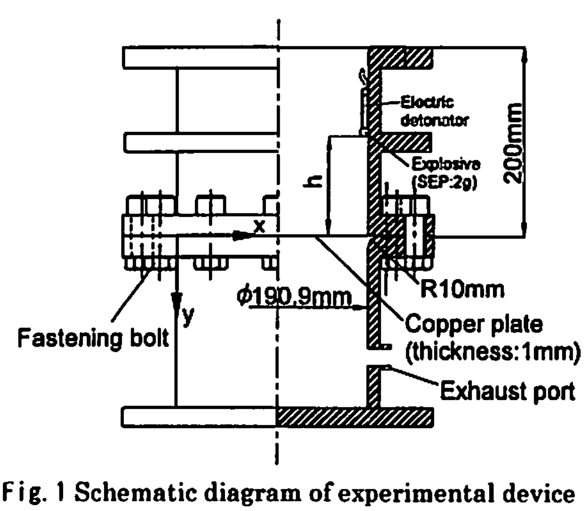


Fig. 1 Schematic diagram of experimental device for the eccentric spherical metal sheet forming.

Table 1 Set-up conditions of explosive position.

No.	Height h(mm)	Horizontal position x(mm)
1	200	190.9(sidewall)
2	150	190.9(sidewall)
3	100	190.9(sidewall)
4	75	190.9(sidewall)
5	50	190.9(sidewall)

three dimensions was performed with measuring system LEGEX 910 manufactured by Mitutoyo Co., Japan.

2.2 Experimental results of eccentric spherical forming.

Figure 2 shows photographs of deformation shape of the copper plate. Fig. 3 shows measurement results of surface shape of copper plate. In these figure, it is can be seen that the explosive was set at right side and below to the copper plate. In case of No.3 to 5, however, left side part of copper plate is more projected than the right side. It can be understood that the projected part of copper plate is larger when the height 'h' is closer. In case of No.5, though the quantity of projection is the largest, the projected part was fractured.

Figure 4 shows a distribution of thickness logarithmic strain of copper plate to the measurement results of surface shape of copper plate (No.4). The logarithmic strain was calculated by measuring the thickness of formed copper plate by micrometer. Figure 4 shows the distribution of thickness logarithmic strain is similar to the formed shape of copper plate.

2.3 Metal pipe forming

Figure 5 shows a schematic diagram of experimental setting for metal pipe forming using underwater shock wave. A copper pipe 150mm in length was on the sheet 1 and 2. The inside and outside diameter were 20 and 22 mm respectively. A detonating cord 250mm in length was set above the copper pipe. Outside and inside diameters of detonating cord were 5.4mm and 4.4mm each. The detonating cord was provided by Japan Carlit Co. The inside of detonating cord was filled with PETN (detonation velocity: 6038 m/s, density: 1200 kg/

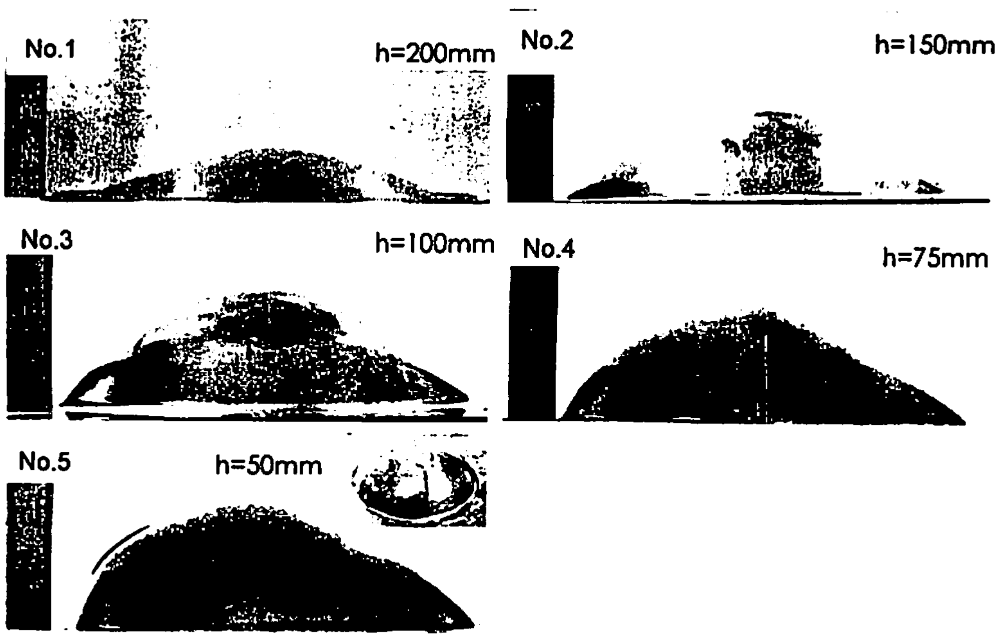


Fig. 2 Photographs of deformation shape of copper plate.

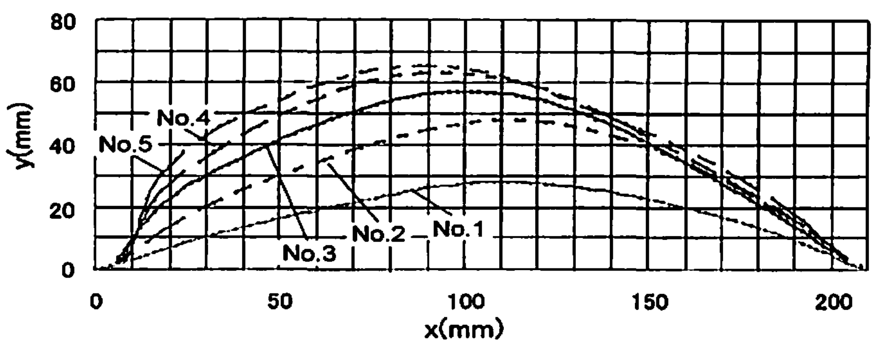


Fig. 3 Measurement results on the surface shape of copper plate.

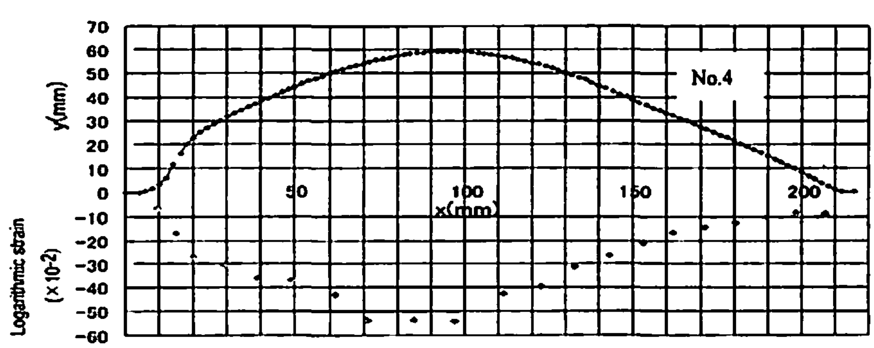


Fig. 4 Distribution of thickness logarithmic strain of copper plate to the measurement results of surface shape of copper plate (No.4).

m^3). 'h' indicated in Fig. 5 is the distance between the bottom of the detonating cord and the top of the copper pipe. These were submerged into a tank filled with water.

Experimental conditions are showed in Table 2. Nine set-up conditions were tested. Both side ends of copper pipe were sealed by rubber cap, adhesive tape or nothing. Inside of the copper pipe were filled with air (hollow), water, air bubble sheet or sand. And then, sheet 1 and 2 are buffers. 'Nothing' of columns of sheet 1 in Table 2 means that sheet 1 does not use. So, the copper pipe set directly on the steel as sheet 2. The distance between the copper pipe and explosive h was changed in from 0 (the explosive set directly on the copper pipe) to 178 mm.

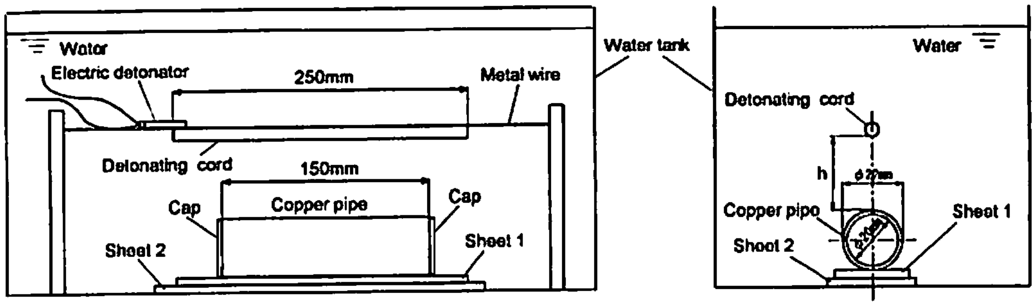


Fig. 5 Schematic diagram of experimental setting for copper pipe forming using underwater shock wave generated by underwater explosion of explosive.

Table 2 Experimental condition of metal pipe forming.

	Closing method of both pipe end	Filling inside of pipe	Sheet 1	Sheet 2	h(mm)
A	Rubber cap	Hollow	Nothing	Steel	178
B	Rubber cap	Hollow	Nothing	Steel	67
C	Rubber cap	Hollow	Nothing	Steel	45
D	Rubber cap	Hollow	Nothing	Steel	23
E	Nothing	Water	Nothing	Steel	45
F	Adhesive tape	Hollow	Rubber	Steel	45
G	Nothing	Cushioning medium (Air bubble sheet)	Rubber	Steel	45
H	Nothing	Cushioning medium (Air bubble sheet)	Rubber	Steel	40
I	Adhesive tape	Sand	Rubber	Steel	0

2.4 Experimental results of metal pipe forming

Figure 6 shows cross sectional photographs of each experimental condition. In all results, the explosive set above the copper pipe. A 10 mm thick cross section of the center of the piped was obtained from each experiment. In experimental conditions A to D, only h was changed. The cross sectional shape of condition A was almost circular, however, the deformation of the top of the copper pipe is larger as h is smaller. In the case of condition D, the quantity of deformation is extremely large. Thus, if h is smaller a very strong underwater shock wave acts on the top of copper pipe and the quantity of deformation is larger. The comparison of filling the inside of copper pipe provided some interesting results. In the case of filled with water (condition E), the cross sectional shape is almost circular. In case of filled with air bubble sheet (condition G), the top of copper pipe is a little flat, and then h is closer (condition H), it can be seen that the top of copper pipe is almost flat and the cross sectional shape looks like a triangle. When a harder material such as sand (condition I) was placed inside the copper pipe, the quantity of deformation was smaller than the other conditions. Even though the explosive was in contact with the top of copper pipe it only deformed slightly and was formed into

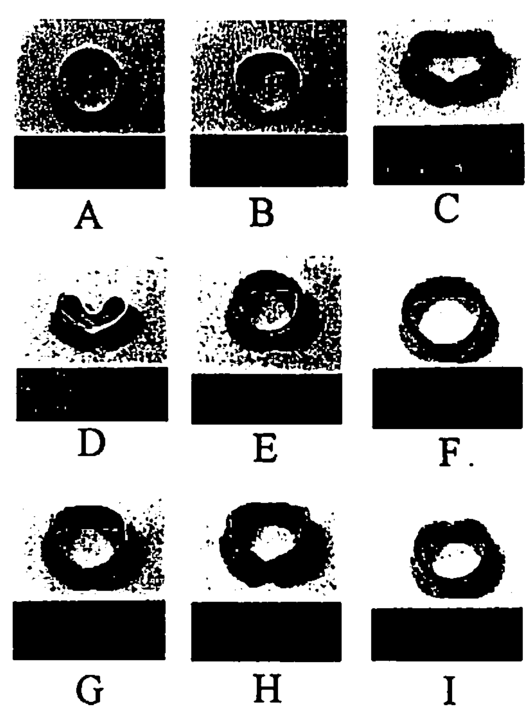


Fig. 6 Cross sectional photographs of copper plate for each experimental conditions.

a heart shape.

3. Numerical study

3.1 Numerical simulation method

Some numerical simulations for free metal sheet forming and metal pipe forming using the underwater shock wave were performed.

Figure 7 shows a simulation model for the free metal sheet forming. In this analysis model, it was assumed to be a two dimensional plane problem and the depth direction was infinite. The explosive was SEP. The size of the explosive was as shown in Fig 7. An x-y coordinate system was arranged as shown in a figure. The blank was 2mm thick copper, and the size of the pressure vessel and die was as shown in the figure. The wall and model of both sides were assumed as rigid bodies. Distance from a left wall to the center of the explosive was set to 'w' and distance from a metal plate to the explosive upper part was set to 'h'. W was fixed at 3mm and h makes it change with 50 and 200mm.

Figure 8 shows a simulation model for copper pipe forming using an underwater shock wave. A simulation field of half of the copper pipe was considered. The simulation method was assumed as a planer problem using two dimentional Lagrangean scheme FDM. The depth of this field was set as unit length. Then an x-y coordinate system as shown in the figure and a half field from center was calculated. The explosive and copper pipe was placed in water. The simulation field was divided radially and concentrically by a rectangular mesh. The distance between the copper pipe and explosive was 23 mm as described in the experimental condition D in Table 2. We considered the explosive was SEP. Sixty-three percent of SEP was PETN. The explosive size was decided in Fig.8.

The basic equation for the numerical calculation are those of mass, momentum and energy conservation in rectangular coordinates.

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

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

$$\frac{\partial \rho v}{\partial t} + \frac{\partial \rho uv}{\partial x} + \frac{\partial \rho v^2}{\partial y} = -\frac{\partial (P+q)}{\partial y} \quad (3)$$

$$\frac{\partial \rho e}{\partial t} + \frac{\partial \rho eu}{\partial x} + \frac{\partial \rho ev}{\partial y} = -\nabla \cdot U\,(P+q) \quad (4)$$

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

$$\nabla \cdot U = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \quad (5)$$

The copper plate is treated as the viscous elastic-plastic material. The constitutive equation of the copper plate is described by the following equation [2],

$$\sigma_p = 20 + 430\varepsilon_p^{0.445} + 2.9\times10^{-3}\dot{\varepsilon}_p + 3.291\ln(\dot{\varepsilon}_p/5.0\times10^{-4}) \quad \text{(MPa)} \quad (6)$$

where, σ_P is the equivalent stress, ε_P is the equivalent strain and $\dot{\varepsilon}_p$ is the equivalent strain rate.

The deformation due to the stresses is dependent of the following motion equations,

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial (P - S_x)}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} \quad (7)$$

$$\frac{\partial v}{\partial t} = -\frac{1}{\rho}\frac{\partial (P - S_y)}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} \quad (8)$$

where P is static hydrodynamic pressure, ρ is density. Sx is stress deviator in r-direction. Sy is the stress deviator along the y-direction. τ_{xy} is shear stress. u and v denote the x and y- direction velocity components, respectively.

The pressure is solved from the following Mie-Grümeisen equation of state[3],

$$P = \frac{\rho_0 c_0^2 \eta}{(1 - s\eta)^2}\left[1 - \frac{\Gamma_0 \eta}{2}\right] + \Gamma_0 \rho_0 e \quad (9)$$

where, ρ_0 is initial density. e is energy, G_0 is Grüneisen parameter, $\eta = 1 - \rho_0/\rho$, c_0 and s are material constants. For the related materials, the values of those constants are given in Table 3.

Table 3 Material constants for water in Mie-Grüneisen EOS.

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

Initial pressures of all explosive elements were given the detonation pressure of SEP, and at later times the pressure of the elements were calculated as the pressure of the detonation products. The pressure in detonation products of explosive is calculated by using the JWL (Jones-Wilkins-Lee) equation of state[4]. The equation has the following expression,

$$P = A\left(1-\frac{\omega}{R_1V}\right)\exp(-R_1V)+B\left(1-\frac{\omega}{R_2V}\right)\exp(-R_2V)+\frac{\omega E}{V} \quad (10)$$

where, A, B, R_1, R_2, C, and ω are constants (or JWL parameters). V is the ratio of the volume of the product gases to initial volume of the undetonated explosive. For the explosive of SEP, those constants were obtained from cylindrical expansion test and are given in Table 4.

Table 4 JWL parameters for SEP explosive.

A(GPa)	B(GPa)	R_1	R_1	ω
365	2.31	4.30	1.10	0.28

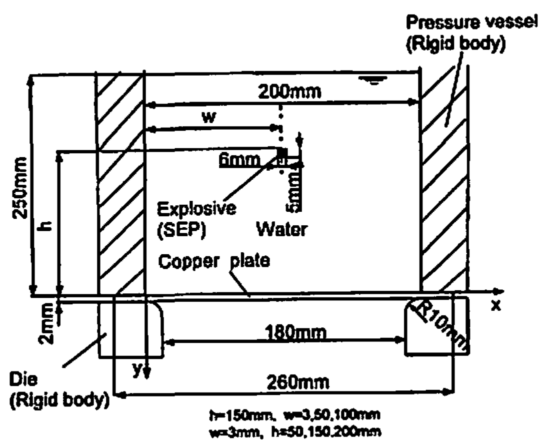


Fig. 7 Simulation model for free metal sheet forming.

For the boundaries involved in the problem, the boundary of water with copper was treated as a

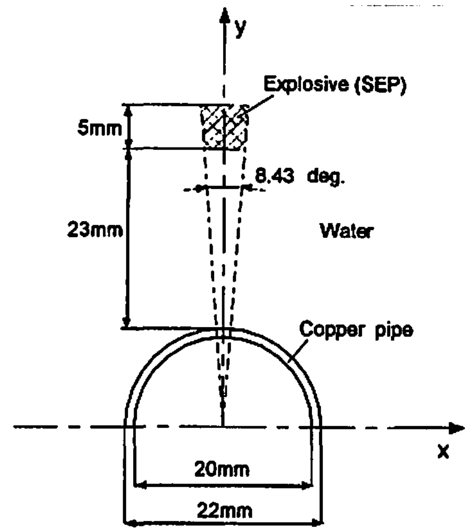
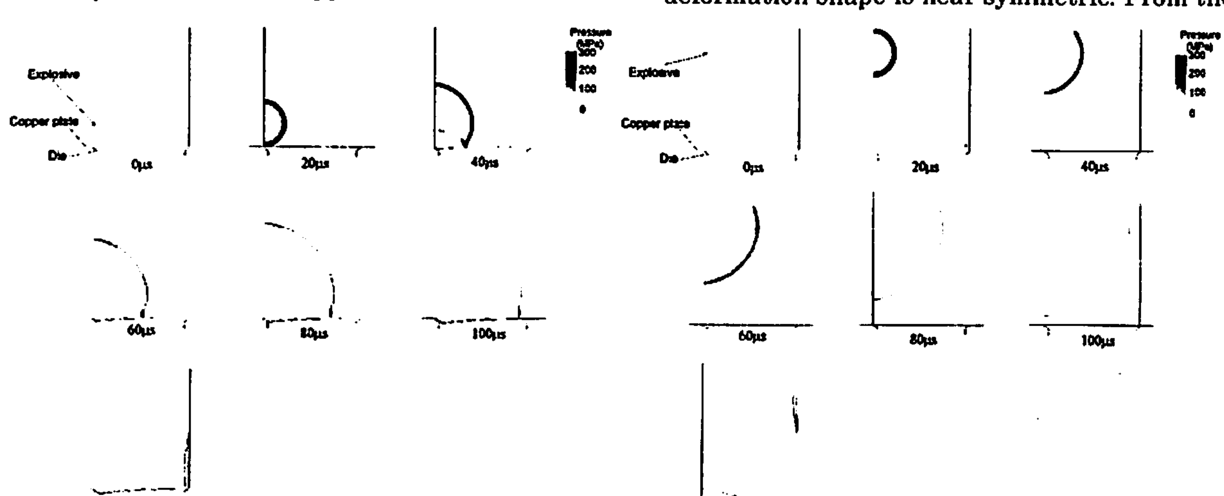


Fig. 8 Simulation model for copper pipe forming using underwater shock wave.

sliding boundary[5], and the surface at the half copper was a rigid surface.

3.2 Numerical simulation results

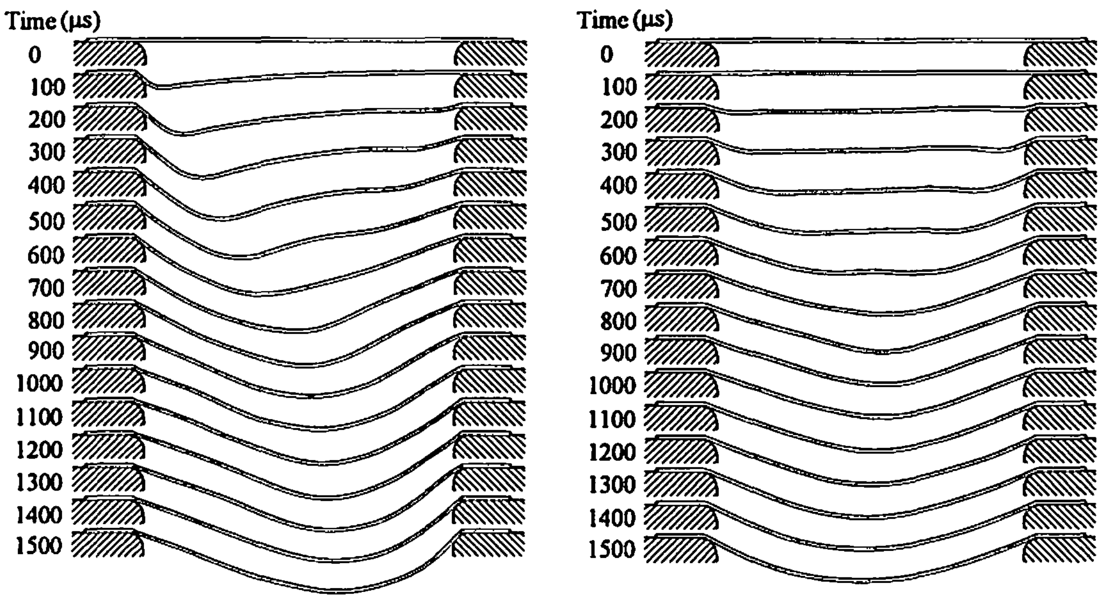
Figure 9 (a) and (b) show pressure contours for metal sheet forming in two cases. Figure 10 (a) and (b) show deformation processes in each case. In the comparison of (a) with (b), the distance from the copper plate to the explosive is closer, a remarkable affect is observed. An interesting result was observed, the deformation shape of the left side (explosive side) of the copper plate was deeper earlier, but at later times the right side of the copper plate was deeper. In the case of (b), the deformation shape is near symmetric. From these



(a) h=50mm,w=3mm

(b) h=200mm,w=3mm

Fig. 9 Pressure contours of free metal sheet forming by numerical simulation.



(a) h=50mm,w=3mm (b) h=200mm,w=3mm

Fig. 10 Deformation process of free metal sheet forming by numerical simulation

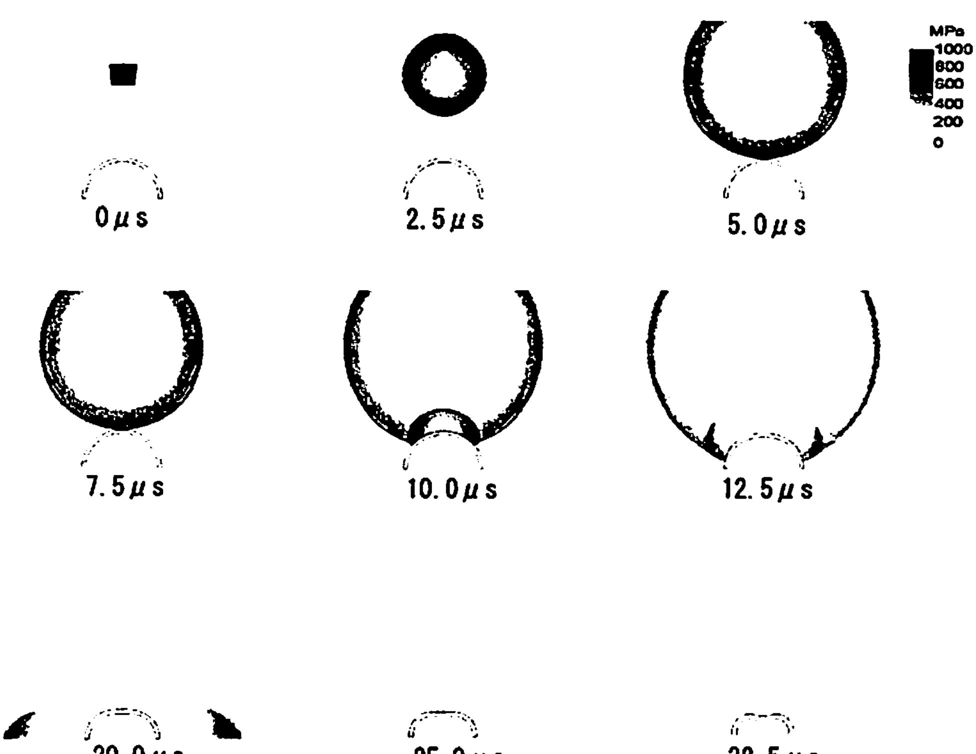


Fig. 11 Pressure contours and deformation process of copper pipe for each times by simulation results.

results, it was understood that if the explosive was set at the sidewall of the pressure vessel and at a moderate height from the metal plate an unsymmetric shape of metal plate could be explosively formed.

Figure 11 shows pressure contours and deformation processes of copper pipe by numerical simulation at interval times. The shock wave generated by underwater explosion was propagated radially, then the copper pipe began to deform after it about 7.5 μs. The achieved pressure of the underwater shock wave reflected and some portion went through the copper pipe. The deformation shape of copper pipe was oval shape at 20 or 25 μs and then, the top of one became dented at 32.5 μs. This shape was of similar tendency to the experimental result of C, D or I in Table 2.

4. Conclusion

The new type of explosive forming, free forming, was investigated. The new method does not require a metal die even for unsymmetrical shapes, which are obtainable by changing the setup position of the explosive. Metal pipe forming was also examined. This method provided a heart shaped cross section of the metal pipe. Numerical simulations using FDM were also performed, simulating metal plate and pipe forming with underwater shockwaves. Some experimental results and tendencies were presented.

References

1) H. Iyama, and S. Itoh, "Numerical Simulation of Free Metal Sheet Forming Using the Underwater Shock Wave", Emerging Technologies for Fluids, Structures and Fluid-Structure Interaction, ASME PVP, Vol.431, pp. 177-183., (2001).
2) S. Tanimura, "Constitutive models for dynamic behavior of metals", Proceedings of International symposium on Impact Engineering, vol.1, p.17, (1992).
3) G. McQueen, S. P. Marsh, J. W. Taylor, J. N. Fritz and W. J. Carter, "The Equation of State of Solids from Shock Wave Studies", in *High-Velocity-Impact Phenomena*, p.230, Academic Press, NY., (1970).
4) E. Lee, M. Finger and W. Collins, "JWL Equation of State Coefficients for High Explosives", Lawrence Livermore National Laboratory report UCID-16189, Livermore, CA., (1973).
5) M. L. Wilkins, "Calculation of Elastic-Plastic Flow", in *Methods in Computational Physics*, Vol. 3, pp. 211-263, Academic Press, NY., (1964).

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