# FORMING OF AL ALLOY PLATE BY UNDERWATER SHOCK WAVE OF EXPLOSIVE


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## ABSTRACT

The fuel cost and efficiency of the automobile greatly depend on the weight. Researches for light weight automotive components are actively being performed, and automobiles using Aluminium alloys instead of steel are becoming more common. However, Al alloys have limited formability in comparison with steel and its final shape is more limited. We have attempted to improve this limited formability of Al alloys by explosive forming technique, which is a particular material processing method. In this method, a shock wave is generated by an explosive and propagated through a suitable pressure medium, e.g. water or air, and deforms a metal plate. We performed numerical analysis using LS-DYNA3D, and compared the results to the experimental observations.



## KEYWORDS:

Sheet metal forming, Material model, Explosive forming method

# INTRODUCTION

Recently, improvement of the automotive fuel efficiency is desired. The fuel requirement of the automotive greatly depends on the weight of the car, and by decreasing the weight of the car we can increase the fuel efficiency. The body material of the car is being changed from steel to aluminium based alloys. The fuel efficiency of a car made by all aluminium based alloys is about 35.5 km/litre. However, forming of aluminium alloys is very difficult due to the limit of the forced restrictions. In this research, the explosive forming of an aluminium alloy was performed to investigate the deformability. A very high deformability by explosive forming of the aluminium alloy is reported.

The explosive forming technique is a material processing method where a shock wave is generated by an explosion and propagated through a suitable pressure medium, such as water or air, and deforming a metal plate, tube, or other object. It provides very high straining of the material and also a suitable plastic deformation. The method tested is called shock bulge forming. The advantages of shock bulge forming are reduced spring back and a high strain rate material processing. The material processing at high strain rate leads to an extremely high deformability of the aluminium based alloys.

# EXPERIMENTAL PROCEDURE

The shock bulge forming experiments were performed at the Shock wave condensed matter research center of Kumamoto University. Figure 1 is a schematic of the experimental setup. Aluminium alloy A5052-O plates with dimensions of 230mmx230mmx1mm thick were used for the investigation.

Table 1 : Static tensile properties and chemical composition of A5052-O Al Alloy

<table>
<tr><th colspan="8">Result of static tensile test</th></tr>
<tr><td colspan="3">Tensile strength [N/mm$^2$]</td><td colspan="2">Yield-strength [N/mm$^2$]</td><td colspan="3">Elongation [□]</td></tr>
<tr><td colspan="3">197.3</td><td colspan="2">89.7</td><td colspan="3">26.7</td></tr>
<tr><th colspan="8">Chemical composition</th></tr>
<tr><td>Si</td><td>Fe</td><td>Cu</td><td>Mn</td><td>Mg</td><td>Cr</td><td>Zn</td><td>Ti</td></tr>
<tr><td>0.09</td><td>0.27</td><td>0.02</td><td>0.02</td><td>2.40</td><td>0.19</td><td>0.01</td><td>0.02</td></tr>
</table>

The explosive SEP, manufactured by ASAHI KASEI Chemicals Co, has a detonation velocity of about 7000 m/s and a detonation pressure about 15.9GPa with a density of 1310 kg/m$^3$. A No.6 electric detonator, also from ASAHI KASEI Chemicals Co, was used for detonating the explosives.

An optical observation shadowgraph system [1,2] was used to evaluate the expansion of the Al plate. The shadowgraph system used in this study is shown in Figure 2. This system uses a technique, also denoted direct projective technique, in which a shadow is created by density change on the detector of the camera. The shadowgraph method is used for visualization of a shock wave or the motion of a wave and has been used for many years. In this work, the streak module of an Imacon468, Hadland Photonics, and a high speed video camera, HPV-1 from Shimadzu corporation, were used to obtain data to calculate the expansion velocity of the Aluminium plate.

After detonating the electric percussion cap, the explosive reacted to generate the underwater shock wave. The shock wave propagated toward, and then deformed the plate. Figure 3 shows photographs of experimental devices.

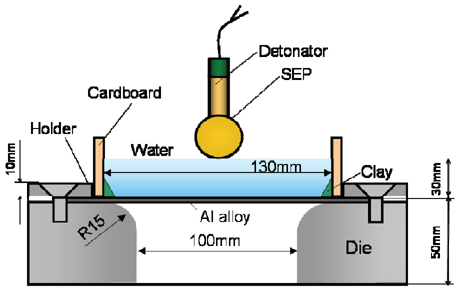



Figure 1 : Schematic of experimental setup

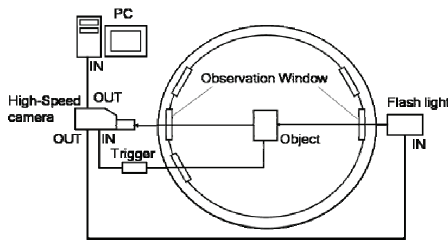



Figure 2 : Shadowgraph method

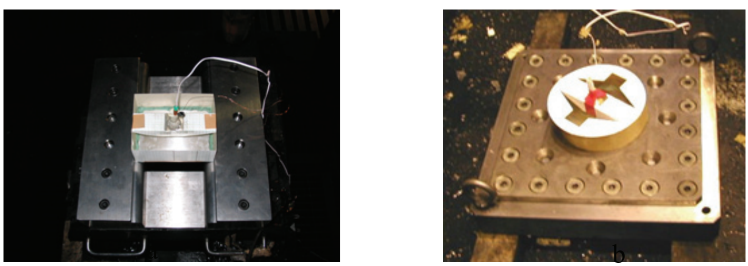



Figure 3: Photographs of experimental device (a : plate, b : circle)

# EXPERIMENT RESULTS

The forming results obtained by the explosive forming experiments are shown in Figures 4 and 5. From Figure 5, the circular grid on the surface of the aluminium plate was used to evaluate the strain. The forming limit was achieved at the amount of 10 g of explosives, and the bulge depth was 39mm. Figure 6 shows a framing photograph and Figure 7 shows a streak photograph of expansion process taken by High Speed Camera.

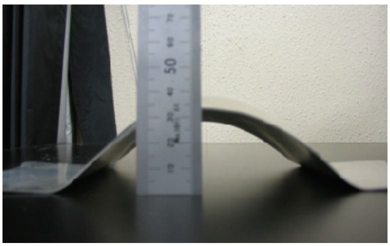


Figure 4 : Forming equipment(plate)

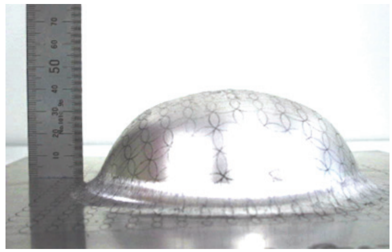


Figure 5 : Forming equipment(circle)

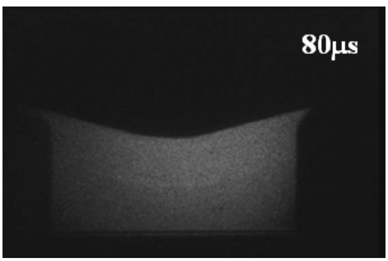



Figure 6 : Framing photograph

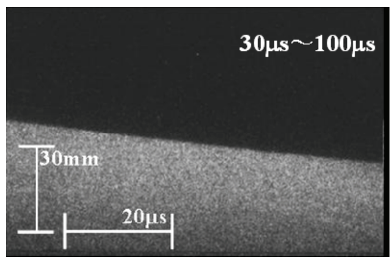



Figure 7 : Streak photograph

# NUMERICAL ANALYSIS

## ANALYSIS MODEL

The phenomenon of explosion and the expansion of the Al plate were evaluated by LS-DYNA 3D. We applied 2-D and 3-D models for analysis, and each model is shown in Figure 8, 9 and 10 respectively. In this numerical analysis, we applied Jones-Wilkins-Lee (JWL) equation of state for SEP and Mie-Grüneisen equation of state for water.

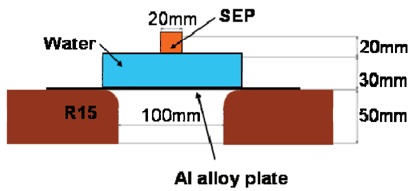



Figure 8 : Numerical analysis 2-D (Plate)

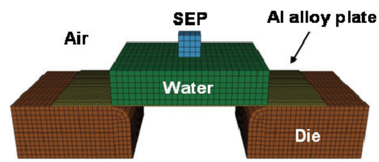
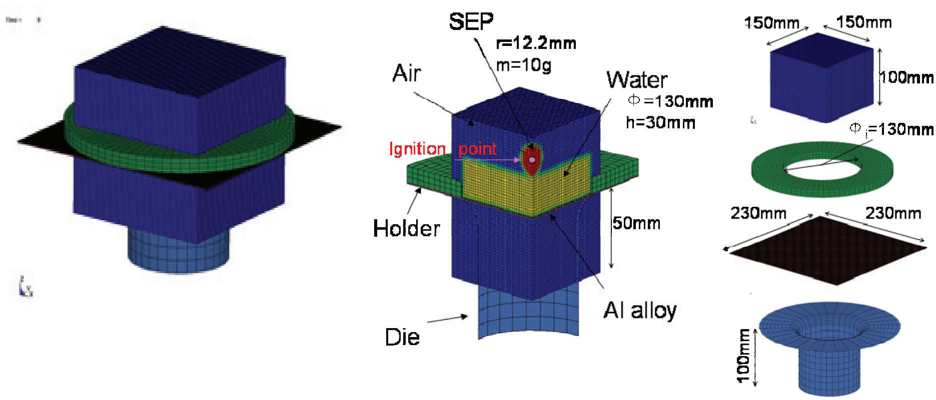



Figure 9 : Numerical analysis 3-D (Plate)




(a) Analysis model (b)Cross-section diagram (c)Deal drawing

Figure 10 : Numerical analysis 3-D (Circle)

# EQUATIONS

The interaction pressure of water and the aluminium sheet was solved by the following Mie-Grüneisen equation of state

$$P = \frac{\rho_0 C_0^{\,2} \eta}{(1 - s\eta)^2}\left(1 - \frac{\Gamma \eta}{2}\right) + \Gamma \rho_0 e \qquad \text{(Eq.1)}$$

where, $\rho_0$ is initial density, $e$ is energy, $\Gamma_0$ is Grüneisen parameter, $\eta = 1 - \frac{\rho_0}{\rho}$ and $c_0$ and $s$ are material constants. Given in Table 2 are the values of the above-mentioned parameters used in the numerical analyses.

Table 2 : Mie-Grüneisen parameter of Water

| | $\rho_0$ (kg/m$^3$) | $c_0$ (m/s) | s | $\Gamma_0$ |
|---|---|---|---|---|
| Water | 1000 | 1490 | 1.79 | 1.65 |

The pressure in the explosive was calculated using the JWL (Jones-Wilkins-Lee) equation of state

$$P = A_{JWL}\left(1 - \frac{\omega}{R_1 V}\right)\exp(-R_1 V) + B_{JWL}\left(1 - \frac{\omega}{R_2 V}\right)\exp(-R_2 V) + \frac{\omega \rho_e e}{V} \qquad \text{(Eq.2)}$$

where $A$, $B$, $R_1$, $R_2$, $C$ and $\omega$ are JWL parameters. V is the ratio of the gaseous products volume to initial volume of the undetonated explosive. For the SEP explosive, the constants were obtained from a cylindrical expansion reference test and are given in Table 3.

The constitutive equation of the Al plate is described in Equation 3,

$$\sigma_y = 72 + 132\varepsilon^{0.28} + 12.8\varepsilon^{0.710} \ln\{\dot{\varepsilon}/(2.0 \times 10^{-10})\} \qquad \text{(Eq.3)}$$

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

Table 3 : JWL parameter of SEP

| | A (GPa) | B (GPa) | $R_1$ | $R_2$ | $\omega$ |
|---|---|---|---|---|---|
| SEP | 364 | 2.31 | 4.3 | 1.00 | 0.28 |

For the calculation of the detonation process of the explosive, the C-J volume burn method was employed. When the volume of the cell of the original explosive in the calculation becomes equal to the volume of the detonation products at Chapman-Jouguet (C-J) state, the solid explosive is assumed to be completely decomposed into gaseous products. Let $V_0$ represent the initial volume of explosive (the reciprocal of the initial density), $V_{CJ}$ be the volume of the detonation products at the C-J state, the reaction rate of the explosive is then simply expressed as

$$W = 1 - \frac{V_0 - V}{V_0 - V_{cj}} \qquad \text{(Eq.4)} \qquad\qquad P = (1 - W)P_g \qquad \text{(Eq.5)}$$

where, W stands for the mass fraction of the unreacted explosive, thus before and after reaction W=1 and 0, respectively, and $P_g$ is the pressure of the detonation products. The pressure P correspondingly was assumed to be equal to that of the detonation products of the partly reacted explosive over the whole cell. The pressure, volume and energy of the reacted explosive are correlated by the JWL equation of state already described above.

## SIMULATION RESULTS

Figure 11 shows the expansion of Al plate and pressure found by the numerical analysis. Figure 12 shows the comparison between the experimental and the calculated result. Figure 13 shows relation between the z-displacement and time, and Figure 14 shows relation between the z-deformation velocity and time.

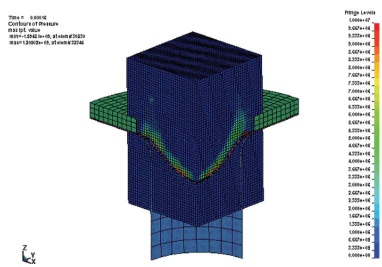


Figure 11 : Expansion modification of numerical analysis

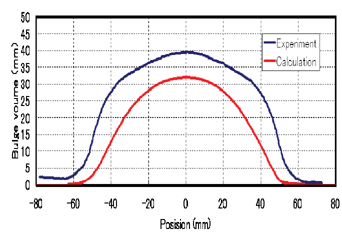



Figure 12 : Comparison between experiment and calculation

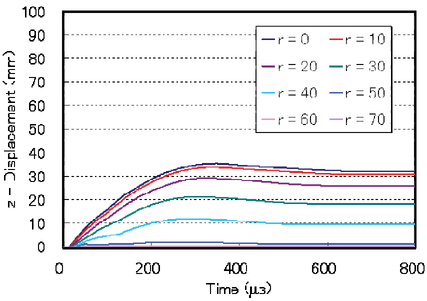



Figure 13 : Relation between
the displacement and time

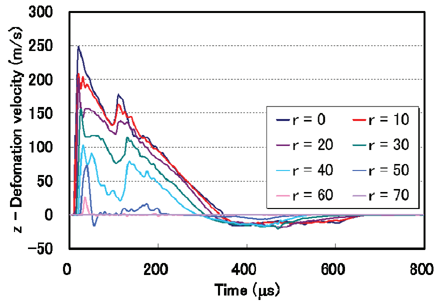



Figure 14 : Relation between
the defomation velocity and time

## SUMMARY AND CONCLUSIONS

In the 2-D case, the expansion velocity is too high compared to experiments. Moreover, the deformation of the plate does not stop.

In the 3-D (plate) case, there is a small difference of the deformation shape.

In the 3-D (circle) case, the amount of deformation and expansion velocity of the plate are roughly in accordance with experiment measurements. Moreover, the spring back is observed.

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