Research paper

Research on explosive forming of magnesium alloy plate using numerical simulation and experimental studies (I)

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Abstract

This study investigated the metal forming of magnesium alloy plate using an intense dynamic loading called as explosive forming. Normally, magnesium alloys have an advantage in terms of strength-to-weight ratio, but it is difficult to perform cold-metalworking through regular metal forming methods. Therefore, explosive forming, which is one of the metal forming techniques with a specific forming mechanism, is employed. The experimantal study is made for AZ31 magnesium alloy plate as to obtain the optimal experimental conditions. It is also performed numerical simulations to estimate the formation of wrinkles and cracks which matches the experimental results.

Keywords: explosive forming, cold working process, magnesium alloy plate, experimental study, numerical simulation

1. Introduction

It is important to conserve energy in the transportation industry, such as aircraft, automobile and railroad. One of the possibilities for energy saving is to use magnesium alloys due to the advantages in terms of strength-to-weight ratio[1]. Magnesium alloys, however, are known as non-ductile material at room temperature, and therefore, it is not easy to perform the cold-working using regular plastic metal forming methods[2)–4)].

Explosive forming method is one of the plastic forming methods with a specific forming mechanism. Once a plate is accelerated by an underwater shock wave generated by an explosive, then, it collides with a die at a high velocity. The workpieces made by the explosive forming method are very precise in shape[5]. There are two type of dies used for explosive forming. One is a concave die and the other is a convex die. In previous studies, the forming with a concave die, which is similar to the stretch forming, is used often for explosive forming. It is easy to conduct experiments with a concave die because fixing the outer periphery of the specimen plate is only needed. However, the specimen plate which has a lower plastic limit often induces cracks at the center of the plate. Therefore, for forming the magnesium alloy (AZ31) plate in the experimental study, Ruan et al.[6] have proposed to use a convex die with spherical surface, and the authors[7] have tried use a convex circular cone die with a trapezoidal shape. The advantage of the use of a convex die is the low elongation of the plate, because the center of the plate is supported by the die during the high pressure generated by the detonation of an explosive.

This study is a continued work of our previous experimental study[7], and the authors are clarified the optimal conditions for AZ31 plate using a convex circular cone die with a trapezoidal shape. Furthermore, the results include the numerical simulations to estimate the formation of wrinkles and cracks which matches the experimental results both for successful and unsuccessful cases with failures. Although the diameter and the thickness of AZ31 plates have kept unchanged in the experimental study, the simulations have possibilities to design the optimal experimental conditions easily even under different conditions. For the numerical simulation, the code ANSYS AUTODYN was employed.

2. Numerical simulation and experimental conditions

2.1 Setup of numerical simulation

According to the setup of experimental study[7], a three-dimensional quarter-symmetry model shown in Figure 1 is used for the numerical simulation in this study.

In this model, cover plate, specimen and die are modeled as Lagrange elements. The material of the cover plate and the specimen plate were Al 1100 and AZ31, respectively. The Mie-Gruneisen equation of state[8] and the Johnson-Cook constitutive law[9] are applied for both plates. The Mie-Gruneisen equation of state are written as

$$P = p_H + \Gamma\rho(e - e_H) \qquad (1)$$

$$p_H = \frac{\rho_0 c_0^2 \mu (1+\mu)}{[1-(s-1)\mu]^2},\ e_H = \frac{1}{2}\frac{p_H}{\rho_0}\left(\frac{\mu}{1+\mu}\right)$$

with pressure P, density ρ, specific internal energy e, $\mu = \rho/\rho_0 - 1$ (where ρ_0 is the initial density) and other parameters as shown in Table 1.

In the Johnson-Cook constitutive model applied to the plates, yield stress Y is estimated by the function of strain ε, strain rate $\dot{\varepsilon}$ and homologous temperature T^* calculated by

$$Y = (A_{JC} + B_{JC}\varepsilon^n)(1 + C_{JC}\ln\dot{\varepsilon}^*)(1 - T^{*m}) \qquad (2)$$

where $\dot{\varepsilon}^* = \dot{\varepsilon}/\varepsilon_0$ is dimensionless plastic strain rate for $\dot{\varepsilon}_0 = 1.0\ s^{-1}$, and T^* is defined by $T^* = (T - T_{room})(T_{melt} - T_{room})$, T_{room}: room temperature, T_{melt}: melting temperature. Although AZ31 has an anisotropic property, the constitutive parameters for rolling direction and transverse direction are very similar at high strain rates[10]. Therefore, the parameters for rolling direction[10]

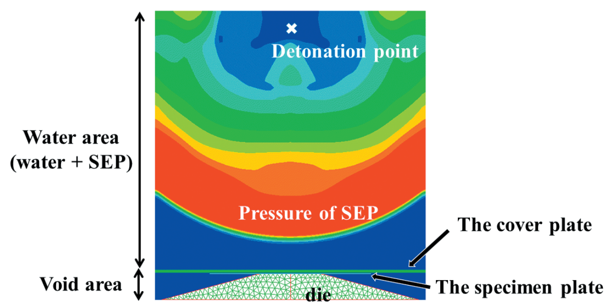

Figure 1 Analytical model.

Table 1 Parameters of Mie-Gruneisen form of EOS based on shock Hugoniot.

	Reference density ρ_0[kg·m^{-3}]	Gruneisen coefficient Γ	Sound velocity c_0[m·s^{-1}]	s
Cover plate (Al 1100)	2707	1.97	5386	1.339
Specimen plate (AZ31)	1775	1.430	4516	1.256

Table 2 Parameters of the Johnson-Cook constitutive model[10].

	A_{JC} [MPa]	B_{JC} [MPa]	C_{JC}	M	N
Cover plate (Al 1100)	49	157	0.016	1.7	0.167
Specimen plate (AZ31)	224	380	0.012	1.554	0.761

Table 3 JWL parameters for SEP explosive.

	A [GPa]	B [GPa]	R_1	R_2	ω
SEP explosive	365	2.31	4.30	1.00	0.28

were used for AZ31 in this study. The variables A_{JC}, B_{JC}, C_{JC}, m and n are listed in Table 2.

It is necessary to keep high vacuum between the die and the metal plate, because the presence of air occurs adiabatic compression. Therefore, there are two areas in this analytical model shown in Figure 1, one is water area from detonation point to the top surface of the cover plate, the other one is void area from the bottom surface of the cover plate to the bottom of the die. The water area including SEP explosive and the void area are considered by Euler element. The equation of state for the Jones-Wilkins-Lee (JWL) equation[11] for the SEP explosive[12] is applied to the model as

$$P = A\left(1 - \frac{\omega\eta}{R_1}\right)\exp\left(-\frac{R_1}{\eta}\right) + B\left(1 - \frac{\omega\eta}{R_2}\right)\exp\left(-\frac{R_2}{\eta}\right) + \omega\eta\rho_0 e \qquad (3)$$

with $\eta = \rho/\rho_0$ and the JWL parameters are shown in Table 3.

2.2 Experimental conditions

The cover plate (Al plate with a thickness of 1.0 mm and a diameter of 84 mm) is set on the specimen plate (AZ31 plate with thickness of 0.3 mm and a diameter of 50 mm) to avoid cracks on the specimen plate and the interface was coated with molybdenum-based lubricant not to induce the joining of two plates. It is necessary for explosive forming method to keep high vacuum between the die and the specimen plate because the presence of air results in adiabatic compression. Therefore, the vacuumed experimental device is covered by plastic tapes and then sunk in the water chamber[7]. The water chamber at Kumamoto University was used to conduct this experimental study.

The dimension of this chamber is 1.5 m in depth, 0.7 m in width, 0.6 m in height. It is noted here that the dimensions of the plates are constant in this study. The other parameters are as follows: leaning of die θ =15, 30, 45 deg, charge of SEP explosive: W = 3, 6 g and distance between the detonation point and cover plate d = 40, 60, 80, 120 mm.

3. Results and discussion

This section shows the experimental and simulation results under the three conditions as listed in Table 4.

Table 4 List of conditions.

	Leaning θ [deg]	Charge W [g]	Distance d [mm]	Remark
Case 1	15	6	80	Successful case
Case 2	30	6	80	Failure case (wrinkles)
Case 3	30	3	40	Failure case (cracks)

Figure 2 Final shape of AZ31 plate for case 1.

3.1 Experimental results

The experimental results obtained for cases 1, 2 and 3 are shown in Figures 2, 3 and 4, respectively. It is found that the condition with leaning of die θ = 15 deg, charge of SEP explosive W = 6 g and distance of the detonation point and cover plate d = 80 mm leads to a desired final shape. On the other hand, for case 2 and case 3, the failure results such as wrinkles at outer circumferential area and cracks near shoulder of die are observed depending upon on the experimental conditions.

The following tendencies on the failure are confirmed.

i) When the leaning of the die is steep, wrinkles tend to occur at outer circumferential area.

ii) When the pressure on the cover plate is high, that is, charge of SEP explosive is large and distance between the detonation point and cover plate is short, cracks near shoulder of die are expected.

iii) No desirable results are obtained with leaning of die θ = 30, 45 degrees. Therefore, the experimental method

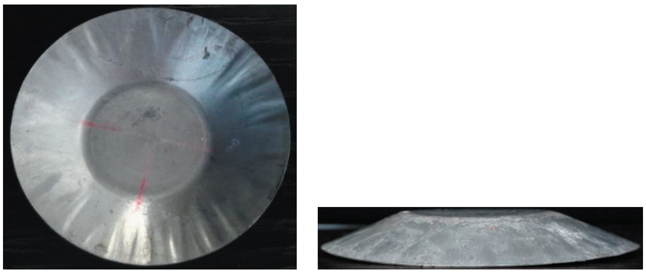

Figure 3 Final shape of AZ31 plate for case 2.

Figure 4 Final shape of AZ31 plate for case 3.

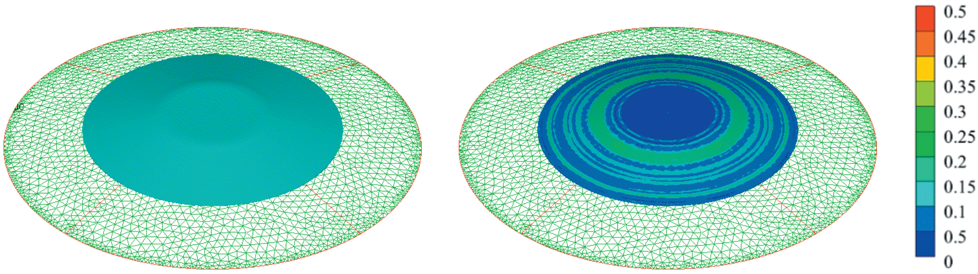

Figure 5 Final shape of AZ31 plate in case 1. (Left: Material location, Right: Effective plastic strain)

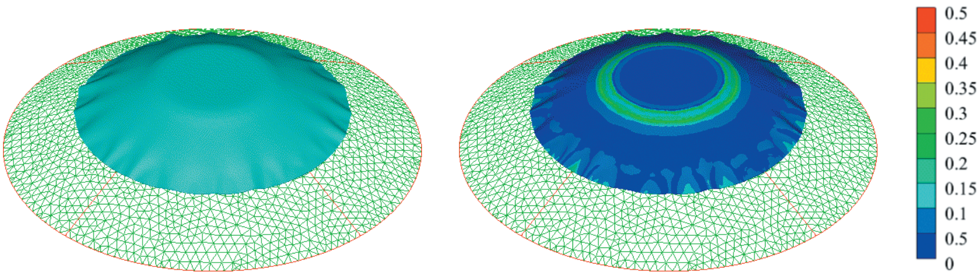

Figure 6 Final shape of AZ31 plate in case 2. (Left: Material location, Right: Effective plastic strain)

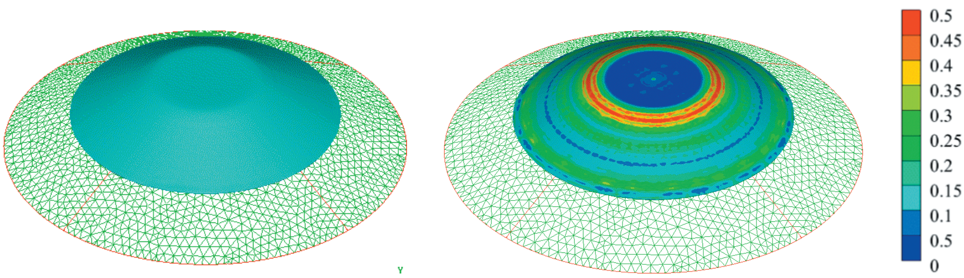

Figure 7 Final shape of AZ31 plate in case 3. (Left: Material location, Right: Effective plastic strain)

should be devised under such conditions in the future work.

3.2 Numerical simulation

The simulated results obtained for cases 1, 2 and 3 are shown in Figures 5, 6 and 7, respectively. The cover plate, the water area and the void area are not displayed in those figures and the right-hand figures are the contour of the effective plastic strain.

Comparing the experimental results with the numerical results, it is found that there are almost identical matches, such as good final shape for case 1 and wrinkles for case 2. For case 3, the value of effective plastic strain near the shoulder of the die is over 0.5 whereas about 0.25 for other cases. Therefore, the simulated result for case 3 suggests the chance to induce cracks in AZ31 plate.

4. Conclusion

This study has investigated the plastic forming of magnesium alloys plate by using explosive forming method and obtained good agreements between the numerical simulations and the experiments. Depending on the conditions, there still remains problems such as the wrinkles at outer circumferential area and the cracks near the shoulder of die. As the future work, authors would like to clarify the optimal conditions based on the prediction using numerical simulation as to obtain the desired final shape in steep case of die by experiments.

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