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Numerical Analysis of the Shape of an Apparatus for Punching Holes in Thin Metal Sheets Using Underwater Shock Waves

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Abstract

Punching is known as one of the methods of making holes in metals. In the punching process, multiple holes can be punched simultaneously, and products can be produced continuously. However, there are also problems such as defective holes when the punch gets worn and damaged. If the punching process is continued with a damaged punch, defective products may be produced continuously thereafter. A clearance is provided between the punch and die to prevent damage to the punch, but this clearance causes burrs and sags in the machined holes. Therefore, we propose a punching process that uses shock waves instead of punches. Using this method, the punch will not be damaged, and the production of defective products can be reduced. In addition, the clearance between the punch and the die is eliminated, and the generation of burrs and sagging may be suppressed. In this study, we developed a pressure vessel to perform the punching process using small shock waves from a thin metal wire explosion. Using the pressure vessel we developed to perform the punching process, we succeeded in punching holes in a thin aluminum plate.

1. INTRODUCTION

Punching is a highly efficient production process. However, if the punches are worn and damaged, subsequent processing may result in the continuous production of defective products. In addition, burrs and sagging occur due to the clearance between the punch and the die. Therefore, we propose a punching process using shock wave. This prevents the punch from breaking, thereby curbing the production of defective products. In such a case, the clearance between the punch and the die is eliminated, and the generation of burrs and sagging may be suppressed. The objective of this study is to perform punching relatively easily and safely using a shock wave generated by a thin metal wire explosion. Therefore, a pressure vessel was developed to apply the pressure generated by the shock wave to the workpiece surface without attenuating it as much as possible.

2. PRINCIPLE OF A FINE METAL WIRE EXPLOSION

Shock waves are pressure waves that travel faster than the speed of sound. When energy is instantaneously accumulated in a localized portion of a medium, high temperatures and pressures commensurate with the magnitude of that energy are generated. The high-temperature, high-pressure portion becomes a wave that propagates beyond the speed of sound and eventually becomes a shock wave.

Electrical energy is stored in a capacitor, and this electrical energy is instantaneously extracted to produce a high-voltage, high-current, short-pulse power. When the high-voltage pulses are supplied to a thin metal wire placed in water by an electronic switch, the metal wire melts and vaporizes in a short time, and a shock wave is generated by the volume expansion of the wire and the vaporization and expansion of the surrounding liquid[1)].

3. SHOCK WAVE GENERATOR

To generate shock waves, it is necessary to supply a large current to a thin gold-axial wire. A Cockcroft-Walton circuit was used to store electricity in a capacitor. The experimental apparatus consists mainly of a Cockcroft-Walton circuit, a thyristor, a charging section, and a charging resistor.

4. SHOCK PRESSURE MEASUREMENT EXPERIMENT

A charging voltage of 2000 V was applied to a 0.5 mm diameter pure aluminum wire, and impact pressures were measured at 40 mm, 50 mm, and 60 mm from the wire. As a result, pressure values of 12.3 MPa, 9.5 MPa, and 6.5 MPa were obtained at 40 mm, 50 mm, and 60 mm from the wire, respectively.

5. DESIGN OF PRESSURE VESSELS

5.1 Method for determining the shape of pressure vessels

Several types of pressure vessels are prepared, and pressure propagation when exploding inside them is analyzed. An actual pressure vessel is fabricated in the shape of the vessel with the highest pressure value acting on the processed surface.

5.2 Setting of explosives

In this study, Ansys Autodyn 19 was used as the analysis tool. Autodyn is an analysis tool dedicated to nonlinear time response analysis of explosions and impacts. Unlike finite element analysis tools that use implicit solvers, Autodyn uses explicit solvers that do not require convergence calculations, making it possible to handle highly nonlinear problems. However, Autodyn does not handle thin metal wire explosions as the source of shock waves. Therefore, we decided to substitute a SEP as the source of the explosion. The analysis was repeated by changing the radius of the sphere, and the shape when the pressure values were close to the experimental values was defined as the explosion source.

5.2.1 Creation of analytical model

Water and SEP are used as materials in this analysis, and the equation of state of Water is defined by the Shock model, which is defined by the Mie-Grüneisen-type shock Hugoniot equation of state[2)] shown as below,

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

where, P is the pressure, ρ_0 is the density at rest, ρ is the density, c_0 is the speed of sound in the medium, e is the initial energy, Γ_0 is the Grüneisen count, and s is the material constant. This equation of state is suitable for the analysis of impact problems, and about 50 material constants are listed in the Autodyn material library. Table 1 shows the parameters of the equation of state entered into the Shock model for Water[3)].

Table 1: Equation of state parameter for water[3)]

Equation of State	Parameters
Reference density ρ_0 [kg/m^3]	1000
Grüneisen coefficient	0
Sound velocity C_0 [m/s]	1647
Parameter s	1.921

Since the plastic state and fracture of water are not considered, constitutive, fracture, and erosion laws were not established.

SEP is newly defined by the JWL equation of state, which is an explosives model and assumes propagation of an ideal detonation at a constant velocity. The JWL equation [4) 5)] of state is shown as below.

$$P = A\left[1 - \frac{\omega}{VR_1}\right]\exp(-VR_1) + B\left[1 - \frac{\omega}{VR_2}\right]\exp(-VR_2) + \frac{\omega e \rho_0}{V} \qquad (2)$$

where P is the pressure of the explosive gas, V is the specific volume, and A, B, R_1, R_2, and ω are the material constants of the explosive. Table 2 shows the JWL equation of state parameters for SEP [6) 7)]. And Figure 1 shows a schematic diagram of the analytical model.

Table 2: JWL equation parameters for SEP[6)7)]

Reference density ρ_0 [g/cm^3]	1.310
Parameter A [GPa]	365
Parameter B [GPa]	2.31
Parameter R_1	4.30
Parameter R_2	1.00
Parameter ω	0.28
C-J Detonation velocity [m/s]	6980
C-J Energy / unit volume [J/m^3]	2.8794x10^9
C-J Pressure [GPa]	15.9

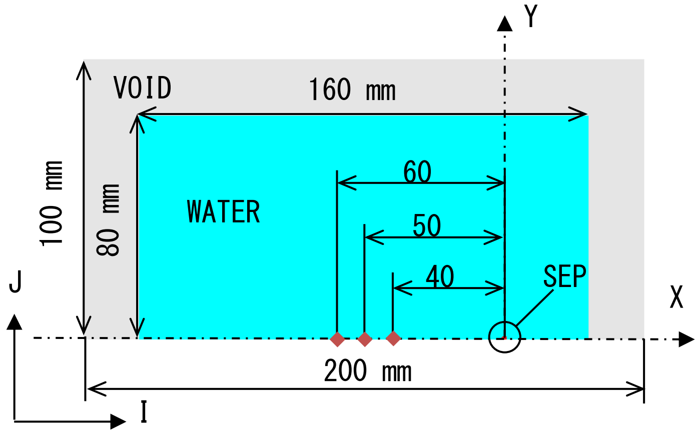

Figure 1: Analytical model

5.2.2 DETERMINED SHAPE OF THE EXPLOSIVE

When the radius of the explosive was set to 1 mm and the mass to approximately 5.5 mg, the pressure at each distance was close to the experimental value. Figure 2 shows the pressure waveforms at each distance output from this analysis, and Table 3 shows the maximum pressures.

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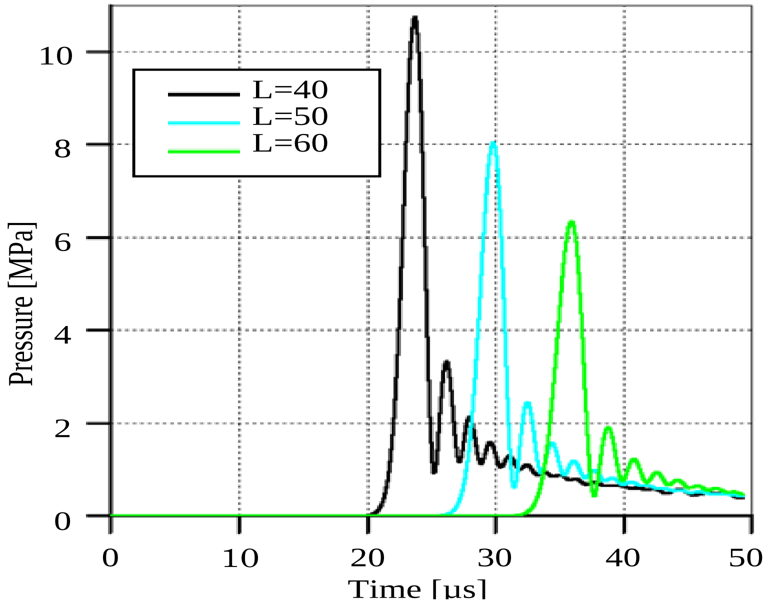

Figure 2: Pressure history

Table 3: Maximum pressures

Distance [mm]	Maximum pressure [MPa]
40	10.8
50	8.0
60	6.3

5.3 ANALYSIS OF PRESSURE PROPAGATION WHEN A PRESSURE VESSEL IS USED

Figure 3 shows a schematic diagram of the analytical model using a pressure vessel.

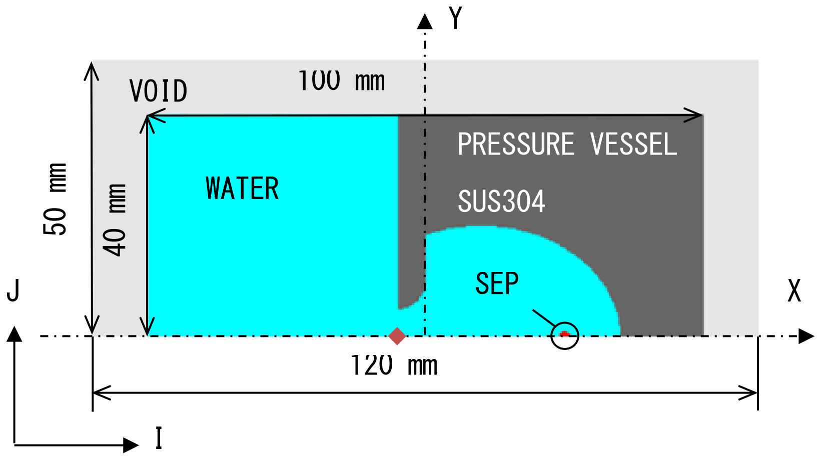

Figure 3: Analytical model; using a pressure vessel.

In this analysis, Water and SEP were the same as those used in 5.2, and SUS304, an existing material in Autodyn material library, was used as the pressure vessel material. The constitutive law was defined by the Steinberg Guinan model, in which the yield stress and transverse modulus of elasticity depend on the state quantity. Table 4 shows the equation of state parameters input to SUS 304[8)], and Table 5 shows the constitutive law parameters[9)].

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Table 4: Equation of state parameters for SUS304[8)]

Equation of State	Parameters
Reference density ρ_0 [g/cm^3]	7.93
Gruneisen coefficient	1.93
Parameter C1 [m/s]	4570
Parameter S1	1.49
Reference Temperature [K]	295.15
Specific Heat [J/kgK]	500

Table 5: Constitutive law parameters of SUS304[9)]

Shear Modulus [GPa]	79
Yield Stress [kPa]	0
Maximum Yield Stress [MPa]	250
Hardening Constant	43
Hardening Exponent	35
Derivative dG/dP	1.74
Derivative dG/dT [kPa/K]	-35040
Derivative dY/dP	0.007684
Melting Temperature [K]	1462

5.4 SHAPE OF PRESSURE VESSEL

In the course of the analysis, it was found that an elliptical shape was effective for the vessel shape [10)]. When an explosion is made at one focal point of the ellipse, it converges at the other focal point and a large pressure value can be obtained. Using this phenomenon, we considered that by placing an explosive at one focal point and a work surface at the other focal point, a punching process could be performed at a large pressure. The closer the distance from the point of detonation to the work surface, the less the pressure decay. However, because the explosion source has an electrode, an extremely small focal distance would cause interference between the electrode and the inner wall of the container. Based on these considerations, the focal length of the ellipse was determined to be 30 mm. The diameter of the punched hole was set to 10 mm in consideration of the machining of the pressure vessel. Figure 4 shows the final determined vessel shape.

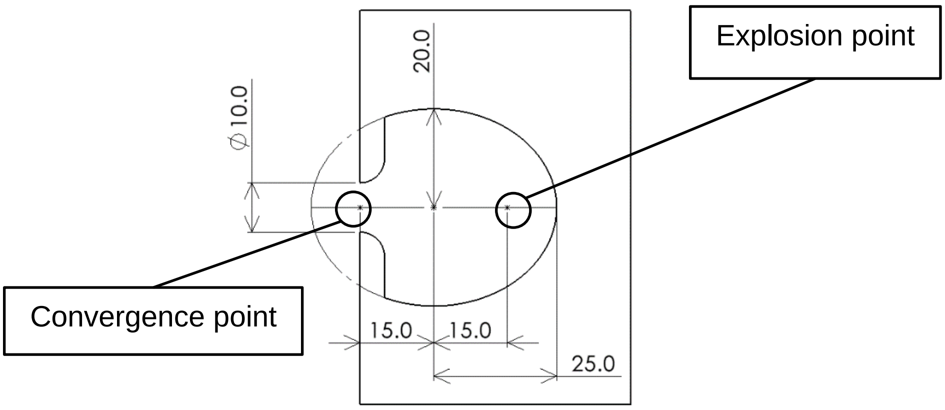

Figure 4: Pressure vessel shape

Figure 5 shows the pressure propagation analyzed using a pressure vessel of this shape. Shock waves traveling in the opposite direction of the workpiece surface are reflected by the curved surface inside the pressure vessel, and the reflected waves converge as they approach the focal point of the workpiece surface. Figure 6 shows the pressure waveforms on the processed surface.

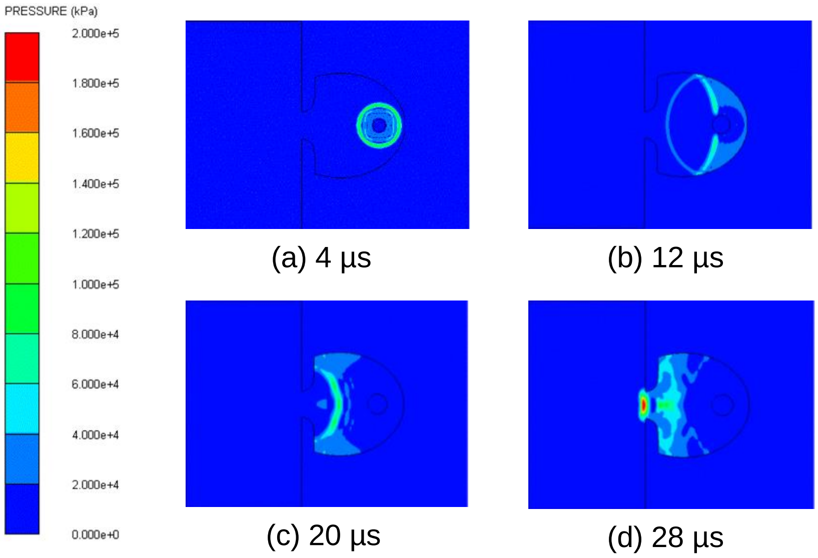

Figure 5: Pressure propagation

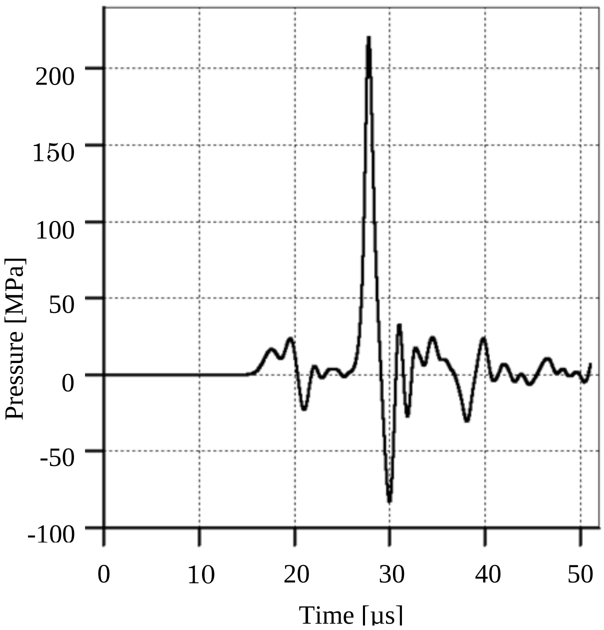

Figure 6: Pressure waveform of processing surface

The design drawing of the pressure vessel actually fabricated is shown in Figure 7. The pressure vessel was designed by dividing it into two parts in consideration of machining. To prevent misalignment of the elliptical joints during assembly, the two parts were positioned by pins. The pressure vessel and die were machined on a 5-axis CNC Machining Center.

A specimen to be punched is placed between the pressure vessel and the die and fastened with bolts. In this state, a shock wave is generated and the specimen is punched into the shape of the die.

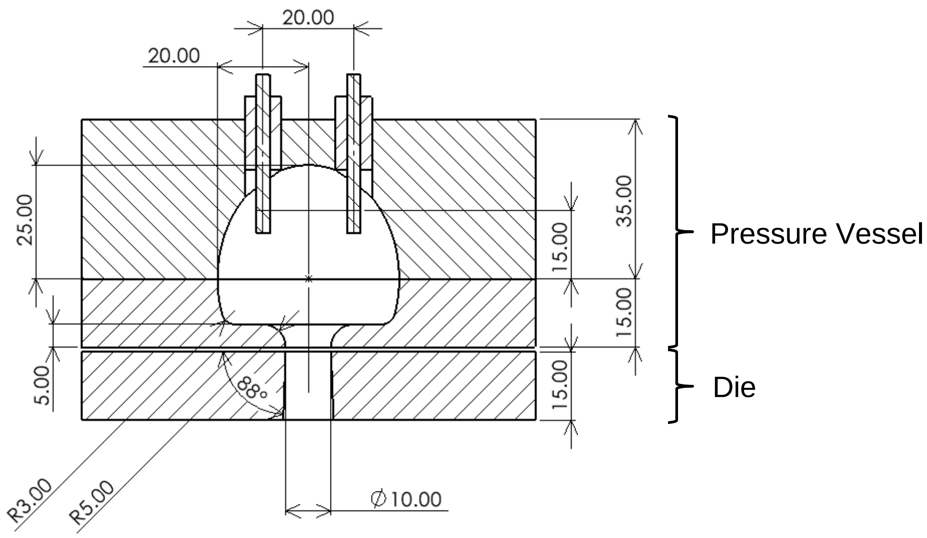

Figure 7: Pressure vessel blueprints

6. EXPERIMENTS ON PUNCHING PROCESS

6.1 EXPERIMENTAL PROCEDURE

A shock wave is generated and the material is punched while a plate is placed between a pressure vessel filled with water inside and a die. In this case, the assembly was performed underwater to ensure that the inside of the pressure vessel was completely filled with water. Water was drained from the die cavity to avoid resistance to punching. Aluminium A1060 was used as the punching material, and different thicknesses of 0.1 mm, 0.3 mm, 0.5 mm, 0.7 mm, 1.0 mm, 1.5 mm, and 2.0 mm were used in the processing.

6.2 EXPERIMENTAL RESULTS

Figure 8 shows an image of a specimen after punching.

As a result, the punching was successful from 0.1 mm to 1.0 mm in thickness. However, specimens of 1.5 mm and 2.0 mm were plastically deformed, but could not be punched out.

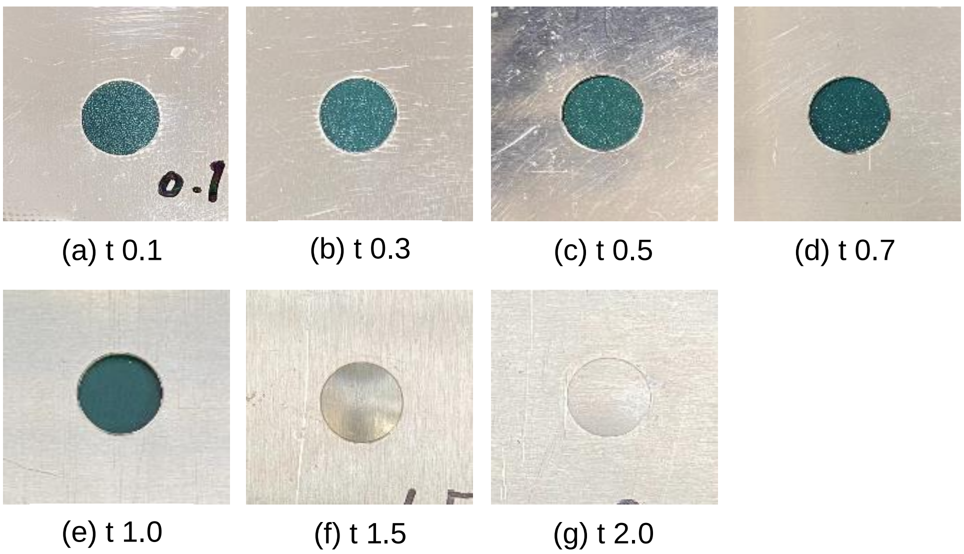

Figure 8: Results of experiments

The pressure required to punch a 10-mm-diameter hole in a 0.1-mm-thick plate is 20 MPa at static pressure. The shock wave generated by the explosion has a first wave that travels directly from the explosion source to the machined surface and a second wave that travels to the machined surface while converging after reflection. Numerical analysis shows that the pressure values of the first and second waves at the work surface are approximately 15 MPa and 220 MPa, respectively. Therefore, in this punching experiment, the pressure value of the second wave acting on the machined surface may have been smaller than the result of the numerical analysis.

One of the reasons why the second wave pressure value did not act on the surface is that the pressure vessel was filled with air. In a metal wire explosion, heat causes the wire and surrounding water to vaporize and expand. Shock waves are less likely to propagate in gases, which have a lower density than liquids. Since the second wave passed through the gas generated in the pressure vessel, it is considered to have been greatly attenuated before reaching the work surface.

6.3 Evaluation of Hole Shape

The burrs and dalliances of the successfully punched specimens are shown in Figure 9.

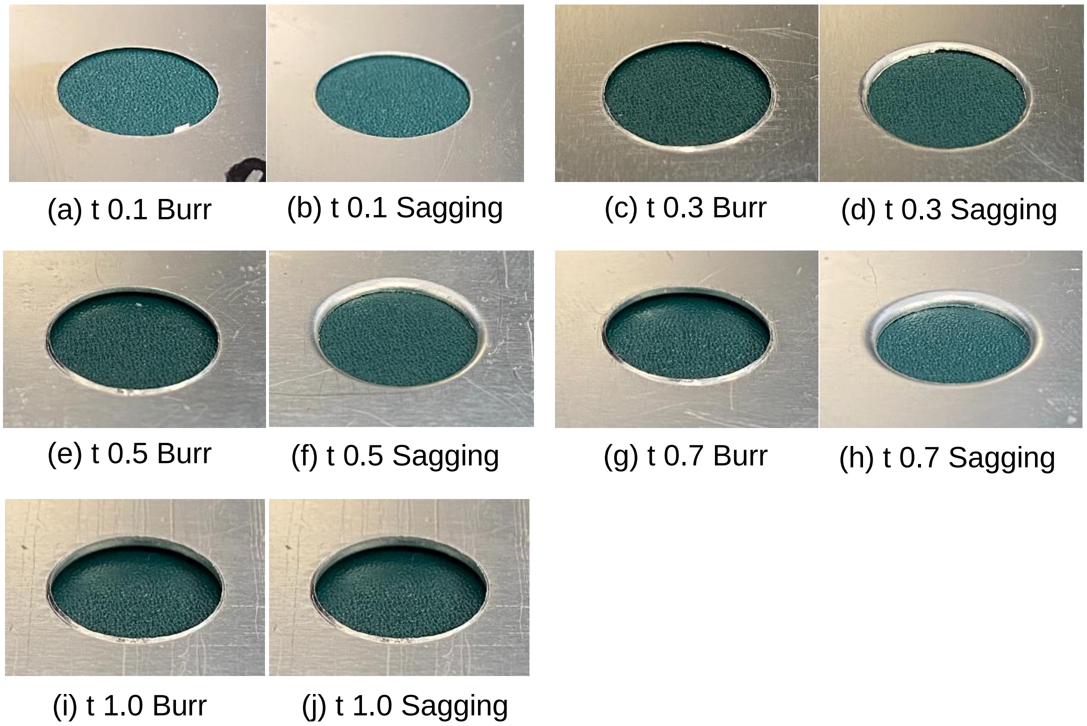

Figure 9: State of burr and sagging

The highest burr was observed on the 0.1 mm-thick specimen, but Figure 9 (a) shows that there was almost no burr on the specimen. Figure 9(b) also shows that there is almost no sagging. Therefore, it can be said that the processing with high enough accuracy is possible for materials with a thickness of 0.1 mm or less.

However, burrs and sagging were observed in specimens with thicknesses from 0.3 mm to 1.0 mm. There was no correlation between burr height and material thickness, but the degree of sagging increased with increasing plate thickness.

The cause of these burrs and sagging is thought to be that the pressure was applied unevenly to the center of the machined surface. This is similar to the punching process when the clearance between the punch and the die is very wide. It is considered that the load applied to the center of the workpiece surface causes bending stress to act on the edge of the workpiece surface, resulting in sagging. In addition, shear and fracture surfaces are observed on the cross section of the hole in the normal punching process using a punch, but no shear or fracture surfaces are observed on the cross section of the hole punched in this experiment. Therefore, it can be judged that the punching was not caused by shear force, but by bending stress and tensile force. In order to suppress the generation of burrs and sagging, it is necessary to apply strong pressure not at the center of the machined surface, but at the edge, so that the material is broken by shear force.

8. CONCLUSION

This study has shown that a thin aluminium sheet can be punched using shock waves from a fine metal wire explosion. Since punching was successfully achieved without the use of explosives, it is expected that punching using shock waves will become easier and safer, thereby improving its practicality. It was also found that holes with good shape accuracy can be punched if the thickness of the material to be punched is 0.1 mm or less. Microholes can also be expected to be punched by changing the shape of the die. If metal foil can be punched with high precision microholes, it may be used in the production of semiconductor package substrates, contributing to higher performance and miniaturization of semiconductors.

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