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Numerical and experimental approach to reduce bouncing effect in electromagnetic forming process using cushion plate †

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Abstract

Electromagnetic forming (EMF) is a high strain rate forming process that uses Lorentz force. In this study, electromagnetic forming with a rectangular block shape in the center of the forming die was examined to determine the possibility and applicability of EMF. However, the high speed of the process in the absence of a medium between the coil and the workpiece results in bouncing of the workpiece, which may result in poor forming. So, in this study, the use of a cushion plate is proposed as a means of reducing the degree of bounce in an EMF process. A 3D electromagnetic numerical model using a spiral forming coil was considered. An RLC circuit, coupled with the spiral coil, was numerically simulated to determine the deformation behavior and design parameters, such as the input current and the magnetic forces. A cushion plate was used between the forming coil and the sheet to be deformed to reduce the extent of bounce. In the numerical simulation, the sheet was found to be well fitted to the objective die with the cushion plate. The simulation results showed that the extent of bounce was drastically reduced because of the velocity direction of the workpiece and the cushion plate. The experiment was performed using 24 kJ to deform Al 1100 with a thickness of 1.27 mm, based on the simulation results. The deformed sheet was well formed, and closely fitted the objective die with a minimum of wrinkling, relative to the results obtained without a cushion plate. As a result, an EMF process with a middle-block die was successfully established both numerically and experimentally to reduce the bouncing.

Keywords: Electromagnetic forming; Lorentz force; Bouncing; 3D FEM; High strain rate forming

1. Introduction

Electromagnetic forming (EMF) is a high strain rate forming technology that is based on the repulsive forces generated by opposing magnetic fields in adjacent conductors. Recently, interest in EMF in the automotive, appliance, aerospace and other fields has been growing as it could feasibly be applied to the forming of aluminum and other materials that are difficult to form [1, 2]. A time-variable current is passed through the coil to generate eddy currents in the workpiece without mechanical contact or a working medium. EMF can be used to form intricate shapes, thereby overcoming the limitations imposed by conventional forming techniques [3-5]. Researchers have focused on developing electromagnetic-mechanical simulation processes. Imbert et al. combined the commercial ANSYS/EMAG and LS-DYNA codes to enable electrical field analysis and structural simulation to predict the electromagnetic forming behavior [6, 7]. A link between the electromagnetic field analysis software and the mechanical field code has been developed [8, 9]. The simulation of the magnetic flux densities during the impulse electromagnetic forming process, with an emphasis on the influence of the field-shaper, was conducted by comparing the 2D and 3D simulation results [11]. Karch and Roll presented a fully transient electro-dynamic structural mechanical coupled simulation for a tube compression process in ANSYS [12]. L' Eplattenier et al. developed a new electromagnetic module, implemented in LS DYNA, which should be well suited to mechanically and electromagnetically coupled tasks. The electrical fields are determined using the finite element method (FEM), while the surrounding air is considered using the boundary element method (BEM) [13]. Demir et al. used the commercially available ANSYS code to perform a three-dimensional calculation of the magnetic field distribution, as well as LS DYNA, which they applied to the calculation of the corresponding workpiece deformation [14]. A numerical method for simulating the electromagnetic forming of low-conduction metals with a driver was performed, and a numerical simulation of EMF for titanium alloy with a copper driver was conducted by Ref. [15]. Recently, an LS-DYN EM module has been devel-

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oped, which allows us to pass source electrical currents through solid conductors and to compute the associated magnetic and electrical fields, as well as to induce currents solved with the Eddy current approximation. In LS-DYNA EM, a module allows us to consider the electrical current and to compute the associated magnetic field and current density, as well as the Lorentz force. The Maxwell equations are solved using FEM for the solid conductors, together with BEM for the surrounding air. The BEM method is very efficient because it does not require the use of any meshes in the air near the conductors. It thus avoids the meshing problems related to the air around the electrical field, which can be significant in the case of complicated numerical simulation geometry models. Even more importantly, the use of the BEM avoids the remeshing problems which arise when using an air mesh around a moving conductor [16]. In this study, electromagnetic forming with a rectangular block shape in the middle of a forming die was examined to determine the possibility and the potential of the application of EMF. In the home appliances field, such rectangular shapes are necessary when forming the pattern in the middle of the panel of a TV or when forming a sharp-edged logo on the surface of a washing machine. In the EMF process, however, bouncing occurs during the forming process due to the extremely high speed and absence of a medium between the coil and sheet. The sheet bounces off the die because there is no medium between the sheet and the die. Therefore, the sheet will not be of the intended shape. In this study, a cushion sheet was inserted between the sheet to be formed and the coil in order to minimize the extent of bounce. To predict the deformation behavior, a numerical simulation model using a spiral coil, forming die, and blank was developed. A 3-D finite element model and sequential coupling simulation method were used to predict the deformation behavior and the coil shape. In the electromagnetic forming simulation, the current density and magnetic flux density of the coil were examined. The Lorentz force, as calculated from the electrical field, was also presented. The forming coil had a 50-mm dead zone and the experiment was conducted using a 11 kV voltage. When the experiment was conducted without a cushion plate, a large bounce occurred, which led to substantial wrinkling in the sheet. With the cushion plate, however, the extent of bounce was significantly reduced and the deformation of the sheet was a good fit to the forming die. Clearly, the cushion plate contributes to reducing the extent of bounce, which improves the forming quality. As a result, an EMF process with a middle-block die can be successfully established by taking a numerical and experimental approach.

2. Electromagnetic forming with middle-block dies

2.1 Prediction of the input current for the EMF process

In the EMF process, the resistance R, inductance L, and capacitance C are important factors for determining the primary input current. This section describes the prediction of the input current for the entire process to calculate the overall system current waveform. The electromagnetic forming machine is regarded as being an RLC circuit. The second order differential equation for the RLC circuit is expressed as Eq. (1).

$$\frac{d^2I(t)}{dt^2} + 2\xi w \frac{dI(t)}{dt} + w^2 I(t) = 0 . \tag{1}$$

Here, I represents the system input current and w refers to the frequency, ξ is the damping factor for the system, and t is the forming period of the EMF process. The value of the primary input current applied through the EMF coil can be expressed by Eq. (2), below.

$$I(t) = \frac{V_0\sqrt{C/L}}{\sqrt{1-\xi}} e^{-\xi wt} \sin(wt) . \tag{2}$$

Here, V_0 represents the system input voltage applied to the forming coil. w and ξ can be expressed using the relationship between R, L, and C, as given by Eqs. (3) and (4).

$$\xi = \frac{1}{2} R \sqrt{\frac{C}{L}} \tag{3}$$

$$\omega = \sqrt{\frac{1}{LC}} . \tag{4}$$

3. Design of EMF process using numerical simulation

3.1 Material model for numerical simulation

An Al 1100-O sheet with a thickness of 1.27 mm was used for the simulation. The constitutive behaviour of the Al 1100-O sheet is described by Eq. (5), as obtained by the MTS Landmark-370 tensile-testing machine.

$$\bar{\sigma} = 180.47\bar{\varepsilon}^{0.20} \tag{5}$$

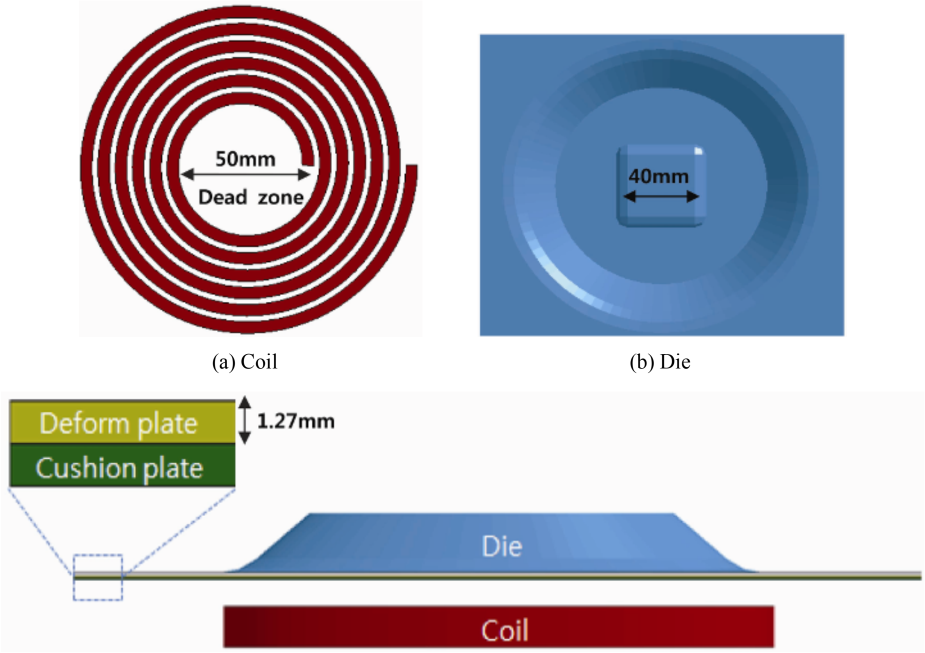
where $\bar{\sigma}$ is the effective stress and $\bar{\varepsilon}$ is the effective strain. In the quasi-static deformation phase, the strain-rate sensitivity is ignored. In the high-speed EMF phase, however, the quasi-static data is scaled to adapt to the high strain rate conditions using the Cowper–Symonds constitutive model which is particularly suitable for high-speed forming simulations.

$$\bar{\sigma} = \sigma_y \left[1 + \left(\frac{\dot{\bar{\varepsilon}}}{p} \right)^m \right] \tag{6}$$

where $\dot{\bar{\varepsilon}}$ is the effective plastic strain rate, p and m are the strain-rate parameters, and is the yield stress that does not consider the strain rate. Here, p = 6500 s^{-1} and m = 0.25 are specific parameters for the AL 1100-O, according to Ref. [9].

3.2 Numerical simulation model for EMF process

The coil is a crucial component, because it delivers the



(a) Coil (b) Die

Fig. 1. Numerical simulation model for EMF process.

force required to deform the sheet. To predict the deformation behavior and the appropriate shape for the forming coil used in the EMF process, an electromagnetic-structural coupling simulation was performed. A 3-D finite element model was created using a spiral coil and an LS/DYNA 970 EM module. A finite element model for the electromagnetic forming process was modeled as shown in Fig. 1. There are four parts: a 6-turn spiral coil, the sheet to be deformed, a cushion plate with a thickness of 1.27 mm, and rigid-body die with a middle block. The size of the blank was 260 mm by 260 mm and the diameter of the forming coil was 140 mm. The dead zone measured 50 mm in the center with a forming depth of 15 mm while the height of the middle block in the forming die was 10 mm. The coil was modeled using eight-node hexagonal solid elements, which are required for the solid conductors in the EM module. The forming die was regarded as being a rigid body since it does not exhibit any plastic deformation. As shown in Fig. 2, a sine-wave current was generated in the forming coil through the application of 11 kV. The total simulation time for the forming process was 500 µs. The system inductance was 5.8 µF and the system resistance was 0.015 Ω.

3.3 Numerical simulation result

To obtain the electromagnetic force, the magnetic flux density and the current density of the forming coil should be considered between the workpiece and the working coil. The current density is given by Eq. (6).

$$\mathbf{J} = -\sigma \frac{\partial A_\theta}{\partial t}. \tag{7}$$

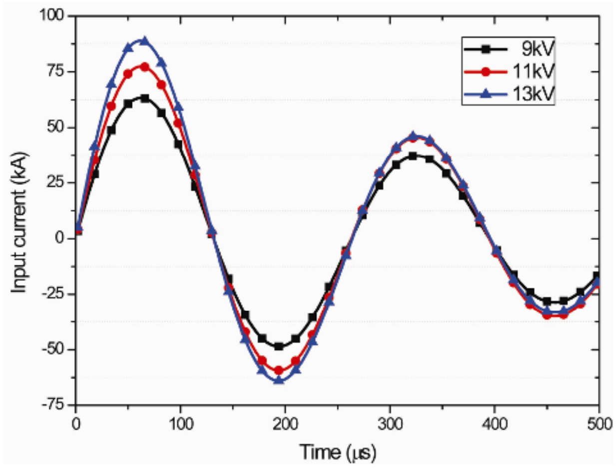
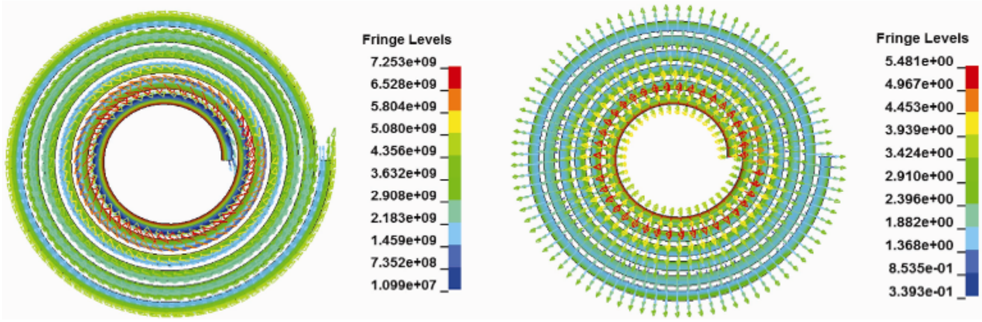


Fig. 2. Input current wave form.

Here, A_θ represents the magnetic vector potential and σ represents the electro-conductivity. In Eq. (7), the current density through the forming coil can be obtained. The electromagnetic force can be calculated from the cross product of the magnetic vector potential B and the current density J in Eq. (8).

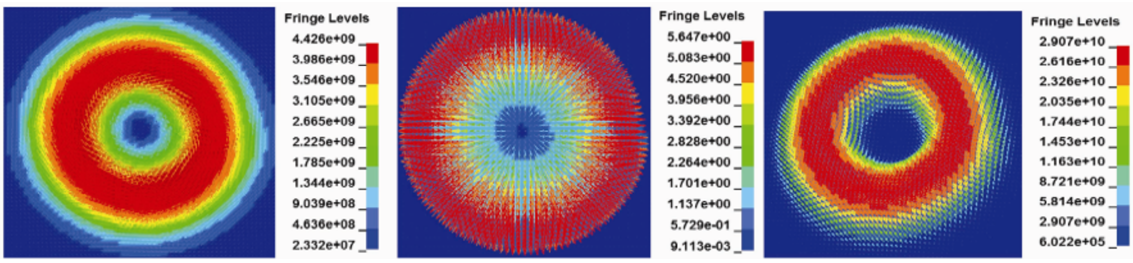
$$\mathbf{F} = \mathbf{J} \times \mathbf{B} \tag{8}$$

Fig. 3(a) shows the top view of the current density vectors of the forming coil during the forming process. As shown in Fig. 3(a), the current density flow around the center of the coil is stronger than in other areas, and the current density vector moves in parallel along the coil. The maximum value of the



(a) Current density (b) Magnetic flux density

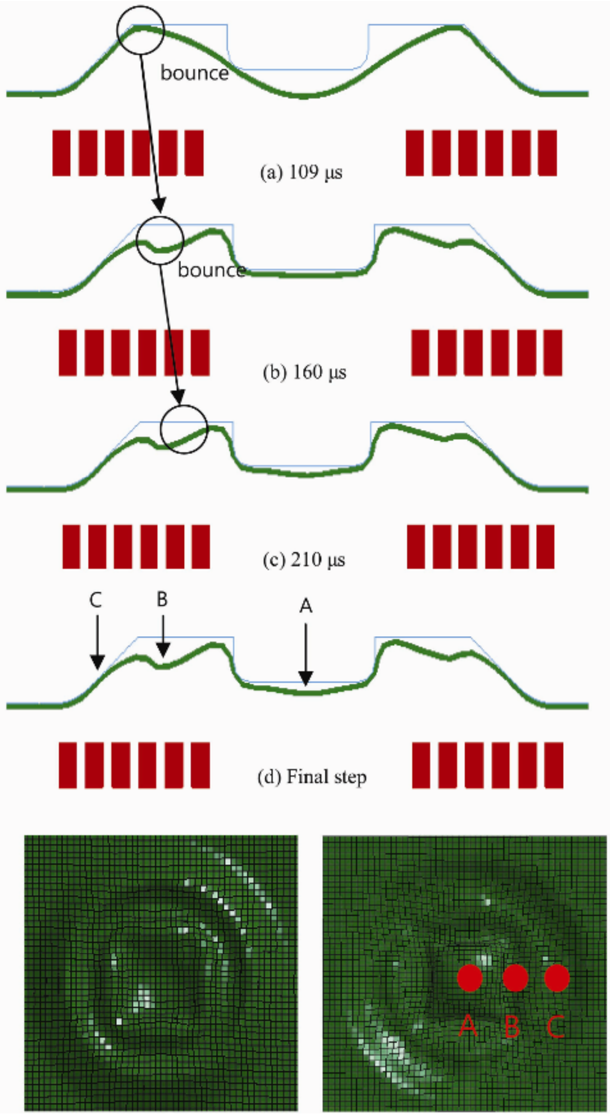
Fig. 3. Top view of current and magnetic density distribution on the forming coil.



(a) Current density (b) Magnetic flux density (c) Lorentz force

Fig. 4. Numerical simulation result on the sheet.

current was $7.25 \times 10^9 A/m^2$ at 64 μs, and the value of the current density reduced with time. The vectors of the magnetic field in the coil are shown in Fig. 3(b). The maximum value of the magnetic field was 5.48 T (Wb/m^2) at 64 μs, and its direction was from the center to the outside of the coil. The current density in the sheet, as generated by the eddy current at 64 μs is shown in Fig. 4(a) and the maximum value of the current density was 4.42 $\times 10^9 A/m^2$. The magnetic field around the sheet at 64 μs is also shown in Fig. 4(b). The maximum value of the magnetic field around the sheet was 5.64 T at 64 μs. In addition, the direction of the current density in the sheet is in the opposite direction relative to that in the coil. Furthermore, given that the magnetic field vectors are perpendicular to the current density vectors, we can conclude that the Lorentz force arises and deforms the sheet as a result of Faraday's law, as shown in Fig. 4(c). The plastic deformation of the sheet at 11 kV at 109 μs, 160 μs, 210 μs, and at the final step is shown in Fig. 5. Figs. 5(e) and (f) show a top and bottom view of the sheet. Severe wrinkling had occurred around the middle-block area due to the bouncing. Fig. 6 shows the Z-direction velocity at points A, B, and C on the sheet; the maximum value was 286 m/s at point B. The sheet around point B starts to bounce at 109 μs and the value of the velocity fell to -198 m/s. The negative velocity continued to 190 μs, so the direction of the plastic deformation of the sheet was in the negative z direction between 109 μs and 190 μs. This velocity direction shows that the sheet does not make good contact with the die without the cushion plate because there is no medium between the sheet and the coil. Consequently, the displacement of points A, B, and C shows that the displacement changed rapidly, creating considerable wrinkling. As a result, the sheet does not make contact with the middle-block die because of the large extent of bounce around point B. Since it is necessary to minimize the bounce to attain good deformation, a cushion plate was inserted between the coil and the sheet as shown in Fig. 8. The cushion plate was also Al 1100 of 1.27 mm. The plastic deformation of the combination is shown in Fig. 8 at 70 μs, 140 μs, and at the final step. The sheets are close to each other at 70 μs but the deformation behavior of the sheets changes at 140 μs. When the sheet to be formed comes into contact with the die, its velocity is higher than that of the cushion plate and is thus deformed well along the die in the final step. A top and bottom view of the deformed sheet is shown in Figs. 8(d) and (e). Relative to the sheet shown in Fig. 8, the wrinkling is clearly reduced and the sheet has come into close contact with the middle block die. The Z-direction velocity is shown in Fig. 9, the velocity near point B is faster than at the other two points, and the maximum velocity is 216 m/s at point B. As shown in Fig. 9, the plastic deformation near point A occurs after that at the other two points because Lorentz force is not applied around point A. So, point A is deformed by effect of inertia, as triggered by points B and C. Fig. 9, most of the velocity was in the upper zero points due to the cushion plate compared with previous result. So, a lesser bounce occurred in comparison with that shown Fig. 6. The velocities of the cushion plate are also shown in Fig. 9 shows that the tendency of



(e) Top view (f) Bottom view

Fig. 5. Plastic deformation of sheet without cushion plate.

the lines is similar to deformed sheet. However, the peak value of the velocity is smaller than that of the sheet to be deformed and the timing is somewhat delayed with the cushion plate. In particular, at point B on the cushion plate, the peak velocity was somewhat less than that of the sheet to be deformed. The velocity at point B on both the sheet to be deformed and the cushion plate shows that, when the velocity at point B becomes negative after contact is made with the die, the high velocity of the cushion plate at point B is still in the positive direction So, the bounce of the sheet to be deformed is drastically reduced as a result of using the cushion plate because the sheets are moving in opposite directions when they collide. In addition, the direction of the velocity at point A is constantly changing during the process. So, the bounce was clearly reduced during the forming process, and the sheet was well fitted to the forming die. At point C, the sheet to be deformed

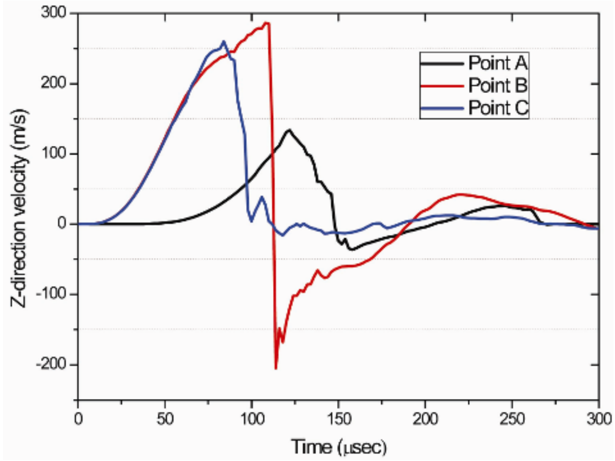


Fig. 6. The Z-direction velocity at point A, B and C on the sheet.

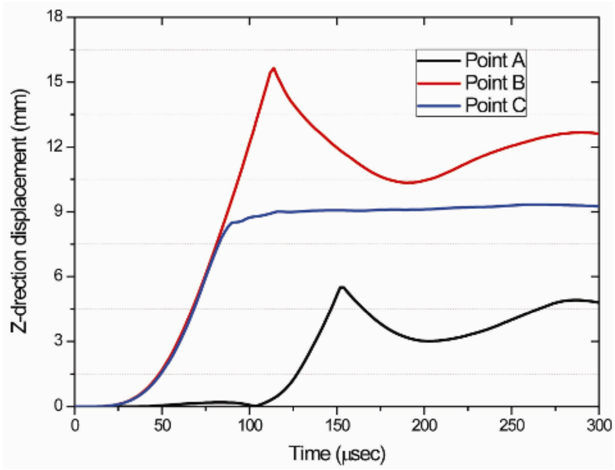


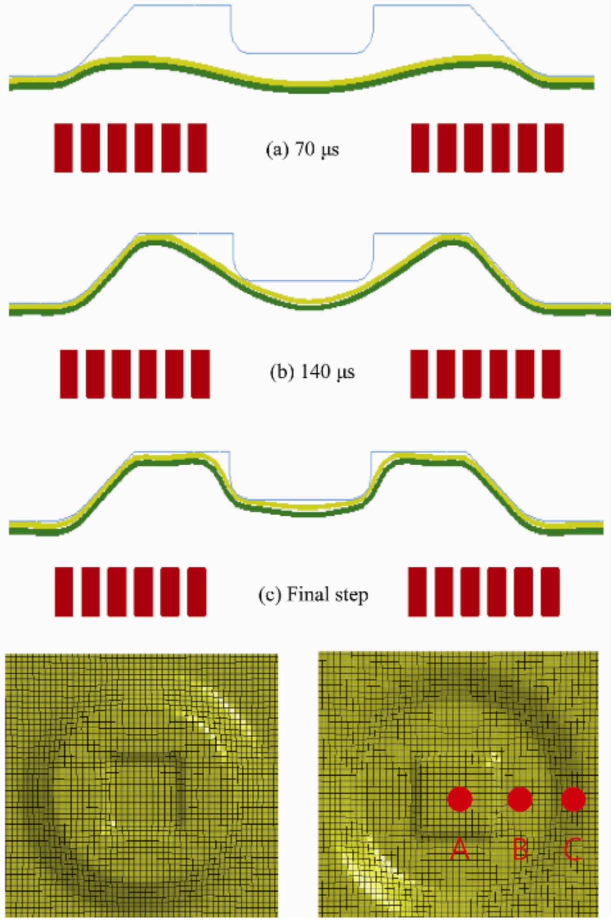
Fig. 7. The Z-direction displacement at point A, B and C on the sheet.

and the cushion plate come into close contact during the forming process. Consequently, the tendency and the value of the velocity are almost the same at any given time. The displacement of the sheet to be deformed, as shown in Fig. 10, shows that the displacement rapidly became saturated to its objective value and most of the forming process had been completed within 300 μs. The displacements at points A, B, and C became well saturated within a very short period of time, relative to Fig. 7, and no wrinkling occurred on the surface. Based on this numerical simulation, we can conclude that the use of a cushion plate in EMF will reduce the bouncing of the sheet.

4. Set up of electromagnetic forming machine for experiment

4.1 Use of EMF with middle-block die to deform the sheet

The forming process using a rectangular block shape in the middle of the die is shown in Fig. 11. The length of the forming area was 140 mm. The total sheet length was 260 mm and the remaining space was filled with insulating material. The



(d) Top view (e) Bottom view

Fig. 8. Final deformation shape of deformed plate.

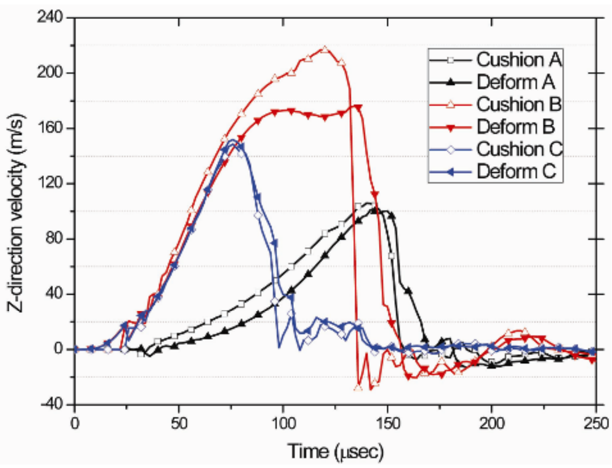


Fig. 9. The Z-direction velocity at point A, B and C on the sheet.

bulge height of the forming die was 15 mm, and the sheet insertion angle was 40°. The rectangular block of the die is positioned in the middle of the die and measures 10 mm high and 20 mm long.

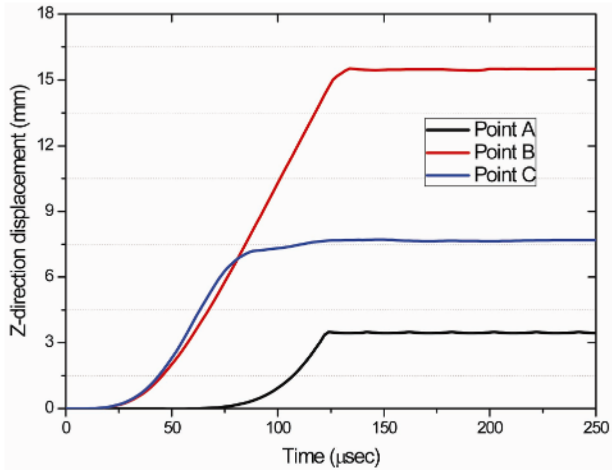


Fig. 10. The Z-direction displacement at point A, B and C on the sheet.

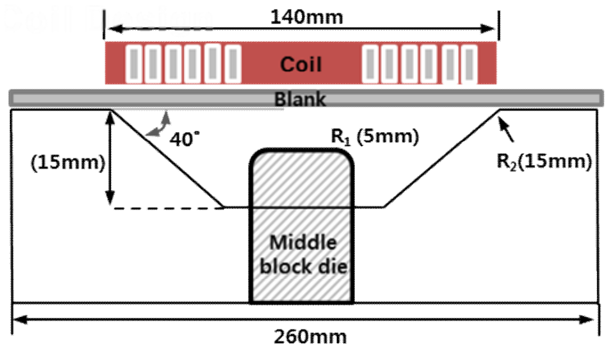


Fig. 11. Schematic view of middle block forming by EMF.

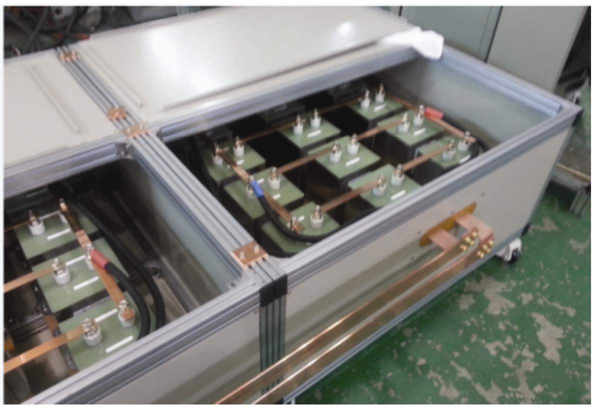
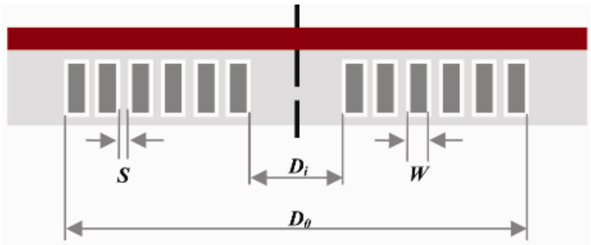


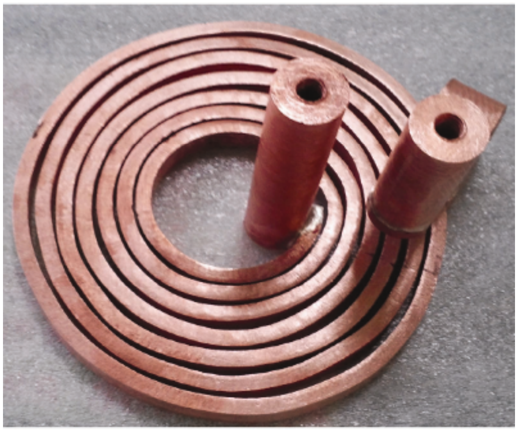
Fig. 12. Electromagnetic forming machine with 32 kJ (PNU_32).

4.2 Design of experimental EMF apparatus

The capacitor is an energy storage device which is used to accumulate an electrical charge in order to create a high current in the forming coil. The capacitor was connected to the coil using a highly conductive flat busbar, as shown in Fig. 12. The amount of stored energy to be used can be controlled from a location remote from the actual forming process. The



(a) Design parameters for spiral type coil



(b) Actual spiral type coil

Fig. 13. Electromagnetic forming coil for the experiment.

amount of energy is given by Eq. (8). Here, the energy U is defined by the capacitance of capacitor C and the input voltage V.

$$U = \frac{1}{2} C V^2 . \tag{8}$$

In the numerical simulation, the electromagnetic forming equipment used to form the sheet with the cushion plate was assumed to use 11 kV and a 333 μF capacitor. The total amount of energy need to deform the sheet was 24 kJ. The forming coil was spiral, with a 50-mm dead zone (D_i =50), based on the simulation results. A schematic of the coil and design parameters is shown in Fig. 13. A copper wire measuring 5 mm (S = 5) 10 mm was used to form the sheet with the middle block die. Insulation films were attached between the forming coils, to ensure a spacing of 2 mm (W = 2). The diameter and the number of turns were 140 mm (D_o = 140) and 6 (N = 6), respectively.

4.3 EMF experiment using a cushion plate

To verify the previous electromagnetic forming results, a forming test using the PNU-32 machine was conducted under the same conditions. The EMF experiment was carried out using Al 1100 with an initial thickness of 1.27 mm. The forming coil was clamped to the upper die with four long bolts after the sheet had been placed on the coil, as shown in Fig. 14.

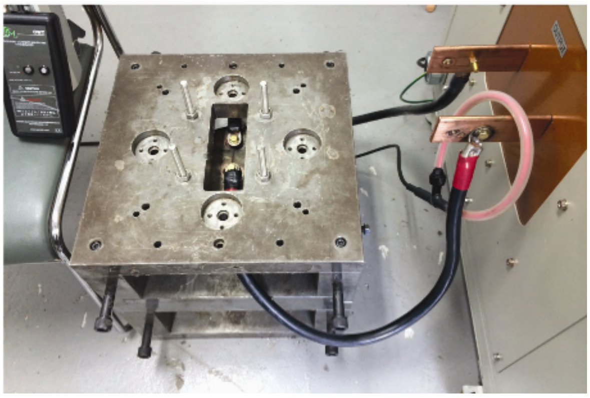
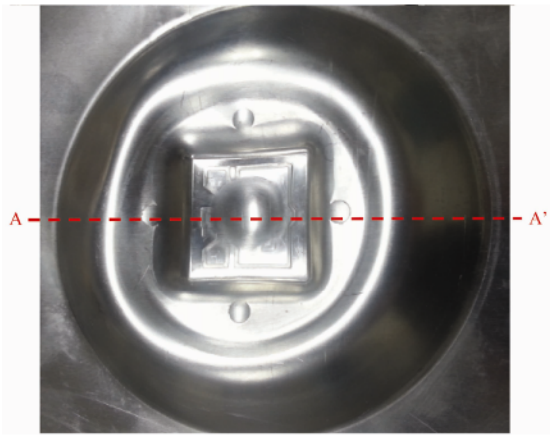
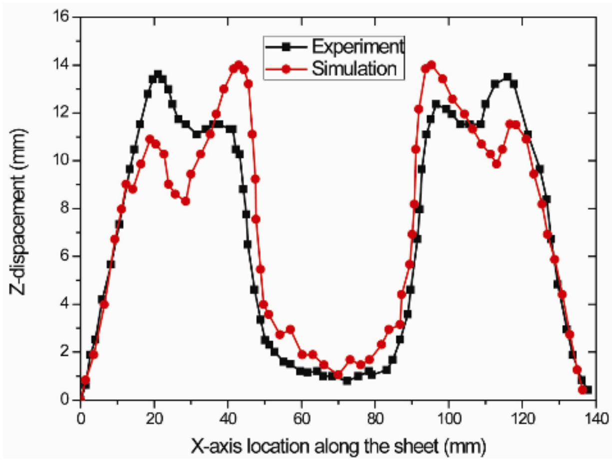


Fig. 14. EMF forming die set coupled with the forming coil.



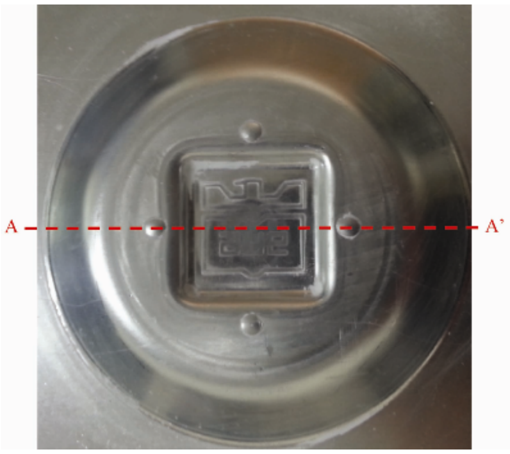
(a) Test without cushion plate



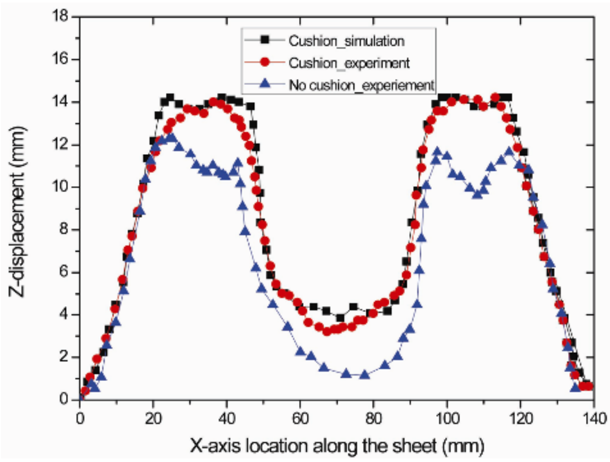
(b) Z-direction velocity without cushion plate

Fig. 15. Experimental result without cushion plate.

With an input voltage of 11 kV, the stored energy was presented as a value of 24 kJ. When the forming was performed A-A' line is measured by 3D scan and shown that the displacement, especially around point B, are have sever wrinkling shown in without a cushion plate, severe wrinkling occurred due to the large bouncing effect as shown in Fig. 15(a).



(a) Test with cushion plate



(b) Z-direction velocity with cushion plate

Fig. 16. Experimental result with cushion plate.

The Z-displacement of Fig. 15(b). So, the formed sheet would not be usable. Therefore, a cushion plate was used to reduce the extent of bounce. The cushion plate was also Al 1100 of 1.27 mm, the same as the sheet to be deformed. Fig. 16 shows the resulting deformed sheet when using a cushion plate at an input voltage of 13 kV. The shape of the sheet, which was well deformed, is shown in Fig. 16(a). The extent of wrinkling was significantly reduced relative to the previous result. The numerical displacement data was compared with the experimental displacement data in the X-direction. The Z-displacement along line A-A', the displacement of the experimental and the simulation results are compared in Fig. 16(b). The measured profile and the numerical final shape are in good agreement, although the height of the simulated part in some locations was slightly greater than that of the experimental result, and the edges were sharper than those obtained in practice. In addition, sever wrinkling is significantly minimize around point B. To sum up, therefore, the use of a cushion plate was clearly superior for an EMF process with a middle-block die.

5. Conclusion

Electromagnetic forming is a high-speed forming technology using pulsed magnetic fields to deform a sheet without any mechanical contact. To successfully design the EMF process, numerical simulation is required to accurately predict the forming process. In this study, an electromagnetic forming process using middle-block dies was examined. A 3D electromagnetic model combined with an RLC circuit was used with an LS-Dyna EM module. First, a numerical simulation without a cushion plate was conducted with LS-Dyna. The simulation result showed that the deformed sheet is a poor fit to the die due to the bouncing of the sheet and the high strain rate. Therefore, a cushion plate was used to reduce the bounce. The use of a cushion plate in the EMF process drastically reduced the bounce given the velocity direction of the plate to be deformed and the cushion plate because the sheets are moving in opposite directions when they collide. A forming test was performed using an EMF machine which had been prepared based on the numerical simulation results. Firstly, an experiment without a cushion plate was performed and this resulted in severe wrinkling because there was no medium between the sheet and the coil. So, a cushion plate was used and the experiment was performed under the same conditions. The experimental results show that the sheet with the cushion plate was well fitted to the die when using 11 kV because the cushion plate reduces the negative velocity of the sheet after it comes into contact with the die. To determine the profile of the sheet, 3-D scanning measurements were also performed. The final shape of the numerical simulation displacement profile was in reasonable agreement with the experimental result. From these results, we can conclude that it is possible to set up an EMF process with a middle-block die by taking a combined numerical and experimental approach.

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Nomenclature

R : System resistance
L : System inductance
C : System capacitance
J : Current density
B : Magnetic flux density
ξ : Energy of a system
I : System current
ω : Frequency factor

W : Input voltage

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