# Produce a large aluminium alloy sheet metal using electromagnetic-incremental (EM-IF) forming method: Experiment and Numerical simulation*

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## Abstract

*The conventional electromagnetic forming processing can't shape large parts due to limitation of the strength of working coil and the capacity of capacitor bank. In this paper, a novel technology named electromagnetic-incremental forming (EMIF) has been proposed. A small working coil moves along the special motion trail and many small electromagnetic pulses energy are used to form a larger aluminum alloy sheet. The effect of vent holes, discharge voltage on sheet final profiles are analyzed. In addition, two discharge times with varying value of discharge voltage is used to obtain better final sheet profiles. The effect of the previous discharge on the second one is also analyzed. Then, a 3D sequential coupling method is used to calculate the magnetic force on the sheet and analyze the forming process. In the latter deformation, the deformation information is also considered from the former one, such as the deflection, velocity, stress, strain, et al. The simulation values are in better agreement with the experimental ones. This work demonstrates that the new technology offers an ability to form large and complex components with a small working coil and small discharging energy of the electromagnetic machine. Moreover, the simulation method can be used for more complex forming system.*

## Keywords

Electromagnetic-incremental forming, Flexible manufacturing, 3D numerical simulation

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# 1. Introduction

Up to now, EMF technology is mainly used for tube bulging, tube compression and tube connection, which has met the industry requirements to some extent. However, for electromagnetic sheet forming, some simple and small parts can only be produced using EMF method. There are some reasons: (1) the magnetic forces in the first current pulse have played a leading role in the sheet forming, while the sheet will make a large deformation for a long time due to inertial effect. It is difficult to control the final deformation results to desired shapes using the conventional electromagnetic forming method, limiting the applications in industry; (2) the bound effect will appear when the sheet impact on a die in a very high speed. It will affect the dimensional accuracy of sheet metal parts; (3) Due to the limitation of strength of the working coil and the capacity of capacitor bank, the electromagnetic forces cannot be arbitrarily enlarged to form large parts [1].

For conventional electromagnetic sheet forming process, the coil stays in a fixed position and the sheet metal deforms in an electric discharge. Aimed to produce large and complex parts for industry application, Multi-step EMF technology may be needed. Vohnout [2] successfully adopted the matched tool-electromagnetic (MT-EM) method to produce an aluminum alloy door panel. Plane strain values in excess of 25%were observed, which are larger than those in conventional stamping. Kamal [3] used electromagnetic forces in a two-step to make a good phone face. In the first step, the uniform pressure electromagnetic actuator is to obtain a very fine surface detail in the part according to the features in the forming die. In the second step, the electromagnetic flanging is used to get greater depth to the phone. However, the simulation approach is not used to analyze the forming processes and obtained optimum parameters for this technology. Shang [4] proposed a new approach, electromagnetically assisted sheet metal stamping, to increase the draw depth of a formed panel. He used multi current pulses (24 pulses) and small discharge energy (5.2KJ) to stretch the bottom area of a panel with small strain by electromagnetic forces. The results show that EMAS did dramatically increase the draw depth without lubrication (44% from 44.0mm to 63.5mm). However, the coil and the punch just move in the direction of drawing depth. If the working coil can move to a special position along three-dimension trajectories, large and deep drawing parts will be produced. In addition, a reasonable numerical simulation method must be proposed to analyze the effect of optimum coil structures, discharge current, motion trajectory and other important parameters on the forming process.

In this paper, based on the electromagnetic assisted sheet metal stamping and single point incremental forming, a new technology is proposes, electromagnetic-incremental forming (EMIF). A small coil and small forming equipment is used to form a lager al-alloy boss. Moreover, a new simulation method is proposed to analyze the magnetic forces and forming process. The effect of the sheet deformation on magnetic analysis is considered. It also puts forward experiment and numerical simulation to prove the feasibly of the new method.

## 2. Principle of Electromagnetic-Incremental Forming

Fig.1 shows the principle of electromagnetic-incremental forming. The forming system consists of energy storage device, working coil, holding device and forming die. Amount of electrical energy is stored in a bank of capacitors which are suddenly discharged releasing all the stored energy. The discharge current runs through a coil which produces intense transient magnetic field around it. According to Faraday's law of electromagnetic induction, when the metal workpiece is placed in a magnetic field, eddy current and magnetic force will be produced in the workpiece. This magnetic force is used to launch the workpiece at a very high speed. Fig.1 (a) shows the initial position for EMIF forming system. Fig.1 (b) describes that the working coil moves to a special position and the workpiece deforms in many cycles of charging and discharging. Finally, the local deformation accumulates into a whole part as shown in Fig.1 (c).

In comparison with incremental forming, a working coil is used to replace the rigid tool. Thus, no mechanical contact between the working coil and workpiece exists and no impureness or imprint occurs on the workpiece surface. In addition, the sheet can be formed at a very high speed in a very short time. Therefore, the EMIF method can improve the formability of sheet metal, the surface quality and the forming efficiency.

In comparison with conventional electromagnetic forming, a small working coil and a small energy device just are required to form large and complex parts according a special coil moving path. Therefore, the EMIF method is a high flexibility forming process.

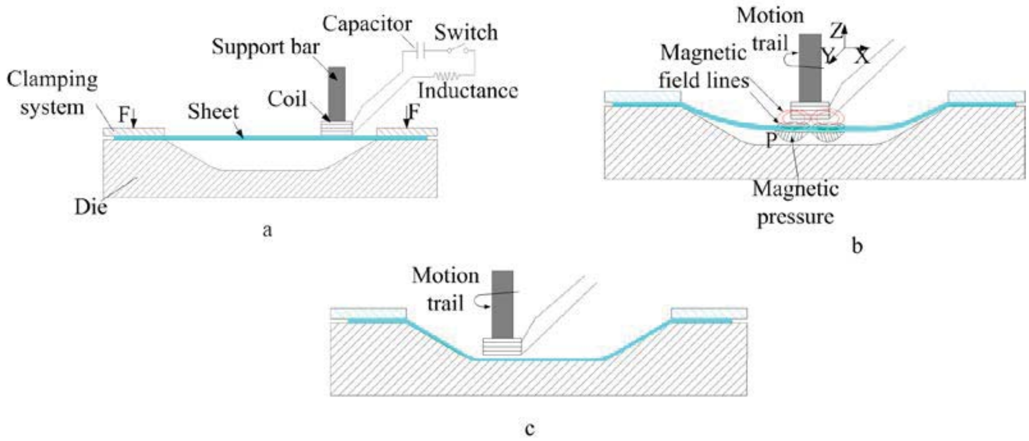



***Fig.1** Principle of electromagnetic-incremental forming*

## 3. Equipment and Experimental Plans

### 3.1 Equipment

The electromagnetic forming equipment used in the experiments is shown in Fig.2. The maximum stored energy is 35KJ with 700μF capacitance at 10KV. The resistance and inductance for the circuit are 4.41mΩ and 13.3μH, respectively. A 6-turn flat spiral coil in conjunction with capacitor banks was used to make the sheet deforms by magnetic force. The section area of the coil is 3mm×6mm. The coil has an inner radius of 12.25mm and a coil separation of 6.2mm.

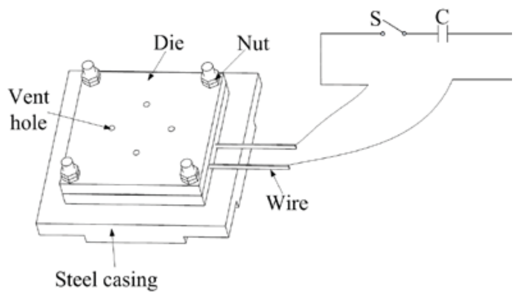
(a) (b)

***Fig.2*** *EMF equipment (a) Capacitor bank and vacuum switch (b) Working coil*

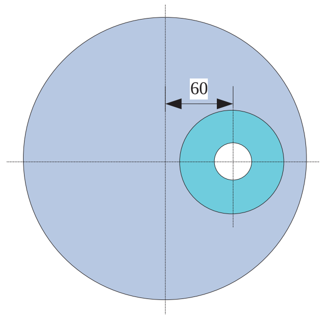
## 3.2 Experimental Program

### 3.2.1 Plan 1

Fig.3 (a) shows the forming system. The coil and the forming die is fixed using screw bolts and nuts. The coil center offset a distance of 60mm from the sheet center (Fig. 3 (b)). Aluminium alloy (AA 3003) sheets were prepared to carry out the sheet forming test. The thickness of the sheet is 1mm. Fig.3 (c) shows the final sheet profile in the condition of discharge voltage is 2400V. It can be seen that a concave pit occurs at the detail region. It may be the air resistance generated by the sheet deforms in a high speed, which affects the sheet deformation.




(a)

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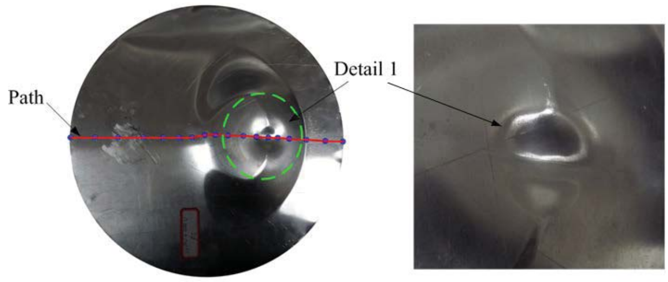
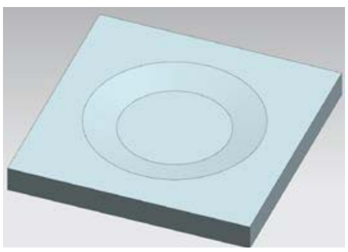


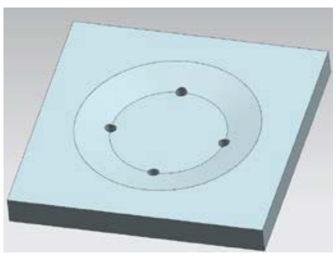

(c)

***Fig.3*** *Plan 1 (a) Schemes of forming system (b) Relative position of the coil and sheet (c) Final sheet profile in 2400V discharge voltage*

In order to prove the air resistance which can affect the sheet deformation, two different die structures are used in experiment test (Fig.4): (1) There isn't a hole in the die; (2) Four circular holes with the diameter of 12mm at the die bottom surface, which is used to reduce the effect of the air resistance on forming process. In plan 1, the effect of vent holes, discharge voltage on sheet final profiles are analyzed. In addition, two discharge times with varying value of discharge voltage is used to obtain better final sheet profiles. The effect of the previous discharge on the second one is also analyzed.



*(a)*



*(b )*

***Fig.4*** *Two different die structures (a) No vent holes at the die bottom surface (b) Four circular holes at the die bottom surface*

**(1) Effect of vent holes on sheet forming**

Fig.5 shows the effect of vent holes on sheet forming. In the condition of no vent hole on the die, the maximum displacement is 6.9mm. If there are four circular holes at the die bottom surface, the maximum displacement is 7.45mm. This shows that a high air pressure is created by the sheet deforms in a high velocity, which hinder and slow the deformation speed. However, with or without vent holes, the sheet cannot stick onto the die bottom surface and the die side surface. This may be the discharge voltage is not big enough to make the sheet impact with the die.

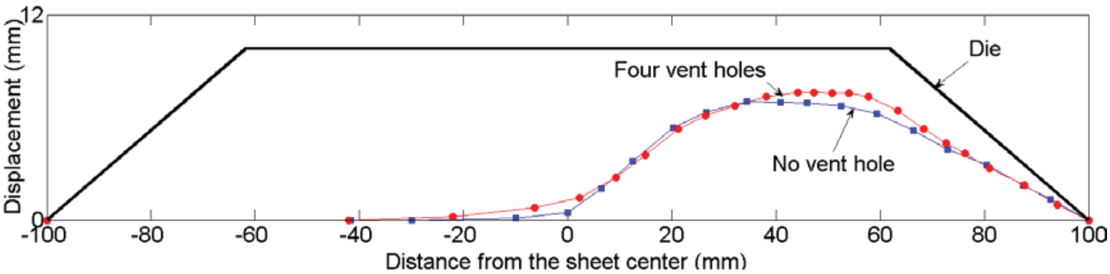



***Fig.5*** *Effect of vent holes on sheet forming*

**(2) Effect of discharge voltage on sheet forming**

The die has four vent holes are used, Fig.6 shows the effect of discharge voltage on sheet forming. When the discharge voltage is 2000V, the sheet has a maximum displacement at the location of 49mm away from the center. When the discharge voltage is 2400V, the maximum displacement is 8.2mm at the location of 60mm away from the center, while the displacement at the location of 49mm away from the center is less than its surrounding area. The reason may be the discharge voltage is too big to make the sheet impact with the die in a high speed and the bound effect appears at the location of 50mm away from the center. However, the sheet sticks onto the die side surface better in a high discharge voltage than the one in the low discharge voltage.

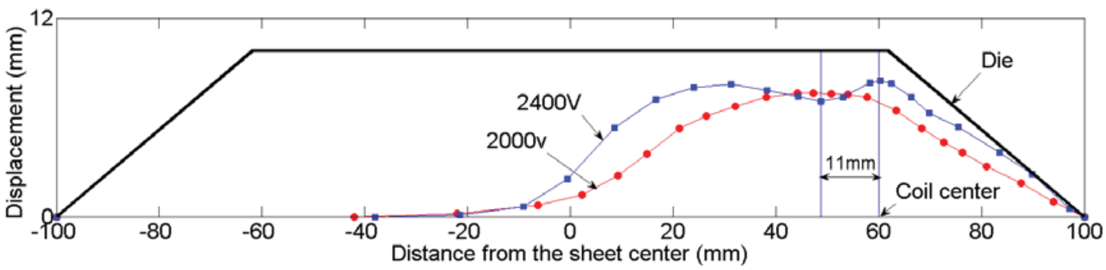



***Fig.6*** *Effect of discharge voltage on sheet forming*

**(3) Effect of the previous discharge on the second one**

According to the experimental results shown in Fig.6, we can conclude that there is an optimum discharge voltage which corresponding to the sheet impact with the die bottom surface and no bound effect appears. However, it will increase the complexity to control the technical parameters for EMIF process. Therefore, the discharging times are increased and the multi-times with varying value of discharge voltage is proposed. Fig.7 shows the final sheet profiles when the discharge times is set to 2. In the first step, large displacements lower than the die depth can be obtained using a small discharge voltage. In the second step, larger electromagnetic forces are used to get greater depth, which make the sheet stick onto the die bottom surface and the die side surface in a high discharge voltage. Under the condition of same discharge voltages, a rough shape is obtained and the sheet doesn't stick onto the die surface when the die has no vent hole. If the same vent holes is used, a rough profile and a concave pit occur at the location of about 50mm away from the sheet center when the discharge voltage are 2400V used in the first step and 4000V used in second step. If the discharge voltage with 2000V use in the first step and 4000V used in second step, a smooth profile has been obtained and the sheet stick onto the die side surface better. However, the displacement in some regions is less than the depth of the die, which reduces the product accuracy. There are two reasons: (a) the number and the dimension of the vent holes don't meet all air out of the die, which causes the remained air still hides the sheet deformation; (b) the designed coil structure and the distance between the coil center and the sheet center is not reasonable.

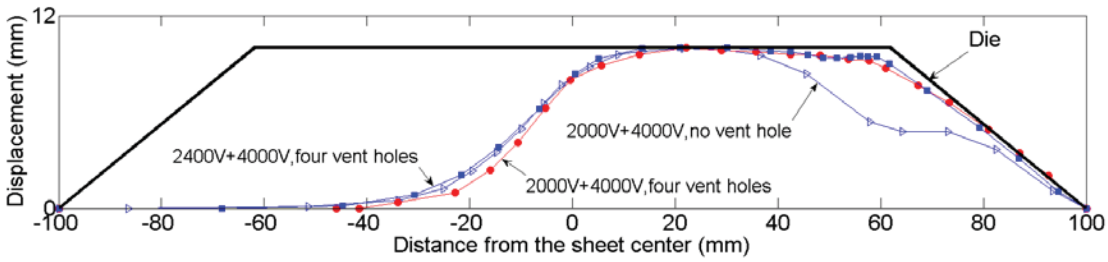



***Fig.7*** *Effect of the previous discharge on the second one*

### 3.2.2 Plan 2

Based on experiment results shown in Fig.5, Fig.6 and Fig.7, the die structure in Fig.4 (b) and the two discharge times in one fixed position with 2000V add 2400V discharge voltages are used in EMIF process. Fig.8 shows the motion trajectory and the coil position. The coil moves to four different positions to form a whole large al-alloy part. In this paper, the move angle is set to 90° and the distances between the coil center and the sheet center are all set to 60mm.

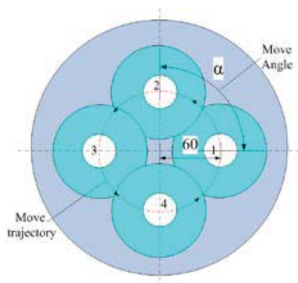
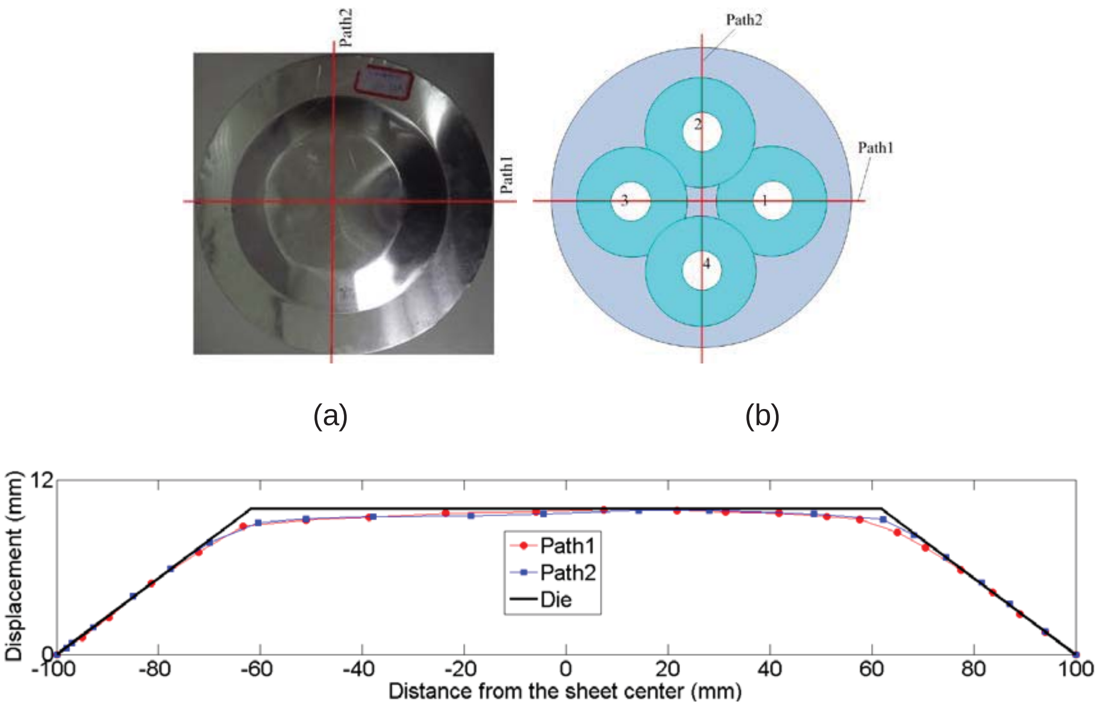



***Fig.8*** *Experiment program of EMIF*

Fig.9 shows the final sheet shapes when the coil moves to four different positions. The data on the deformed sheet along the two paths shown in Fig.9 (a) is used to estimate products quality. The sheet has a good moldability with the die side surface and the sheet shape is similar to the die structure. However, the displacement in some regions is less than the depth of the die, which affects the product accuracy. Nevertheless, we do conclude that the EMIF technology is feasibly to produce a large part with small working coil and small discharge energy. In the future work, our task is how to improve the product accuracy.




(a) (b)

(c)

***Fig.9*** *Final sheet profile using EMIF method (a) final sheet profiles; (b) schematic diagram; (c) Results analysis along two paths*

## 4. Sequential Simulation of EMIF

### 4.1 Flowchart of the implemented algorithm

Since the different sheet regions are deformed sequentially and the air region in FEM must be considered for EMIF, it has many different with incremental forming or conventional electromagnetic forming. And the presented simulation method is more complex than the tradition EMF simulation method due to the coil moves along a path

[5]. Fig.10 shows the numerical scheme for the EMIF process. N is the moving times for the working coil. $T_0$ represents the whole simulation time when the coil in a fixed position. $N \times T_0$ is the total simulation time for EMIF. In this paper, N is equal to 4. When the coil stays in a fixed

position, the simulation time for sheet forming in 2000V and 4000V are 1000μs and 1000μs, respectively. In other words, $T_0$ is equal to 2000μs.

The FEM software ANSYS/EMAG is used to analyze the magnetic force on the sheet. Then the force is imported into ANSYS/LSDYNA using solid 164 element type to predict the sheet forming process. When the coil moves to a special position, the sequential coupling method is used to calculate the magnetic force on the sheet and predict the forming process again. In the latter deformation, the deformation information is also considered from the former one, such as the deflection, velocity, stress, strain, et al. According to the deformation characteristics, the EMIF process can be regard as a "multi-step" forming process using a single coil.

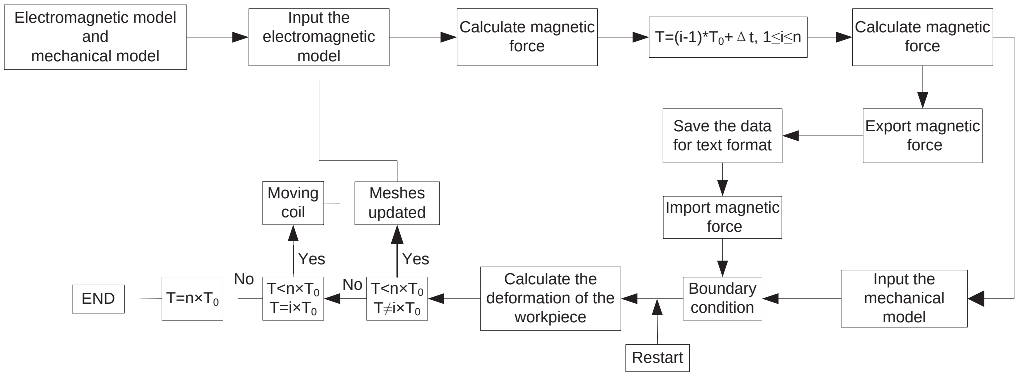



***Fig.10*** *Flowchart of the implemented algorithm*

### 4.2 Simulation results

When the coil moves to four different positions at different time, Fig.11 and Fig.12 show the deformed sheet meshes and magnetic force on the sheet at different time, respectively. In the simulation process, the effects of the sheet deformation and the coil moving on magnetic field analysis are both considered. This shows the simulation method has high computation accuracy for EMIF process. In addition, the simulation method can also be used for more complex 3D forming system, which solves the bottleneck problem in numerical simulation of electromagnetic forming.

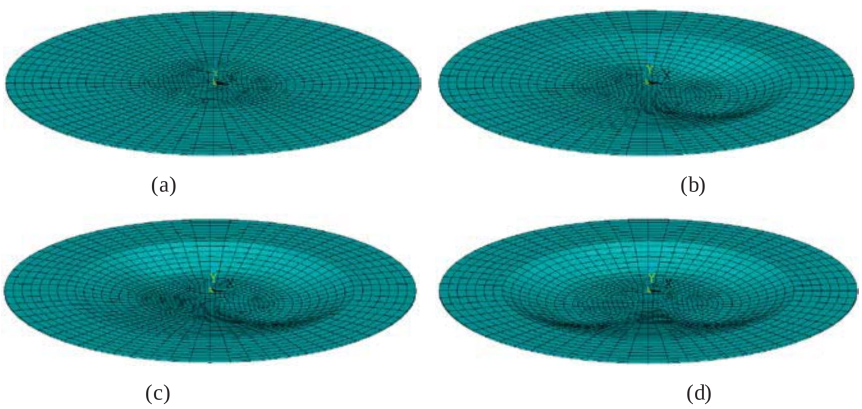
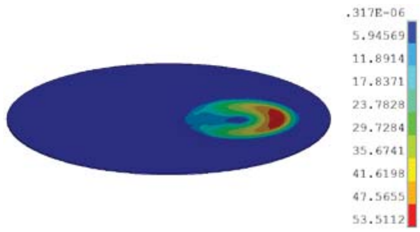
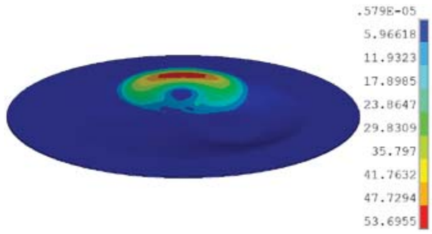


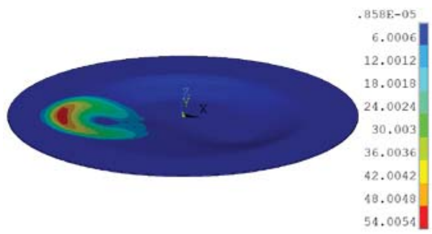

***Fig.11*** *Deformed sheet at different time (a)t=150μs, (b)t=2150μs, (c)t=4150μs, (d)t=6150μs*



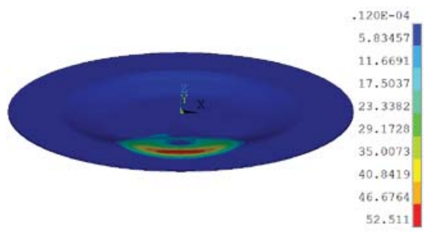

(a)




(b)




(c)




(d)

***Fig.12*** *Magnetic force (N) at different time (a)t=150μs, (b)t=2150μs, (c)t=4150μs, (d)t=6150μs*

Fig.13 shows the sheet profiles in path 1 in 2000V discharge voltage when the coil stay in a fixed position. At the time of 1000μs, the maximum displacement, 7.3mm, at the location of 43.5mm away from the sheet center is observed. Based on the results in Fig.6, the maximum displacements are also not located at coil center. This shows the deformation process of EMIF is totally different with the one of traditional EMF due to a distance between the coil center and the sheet center.

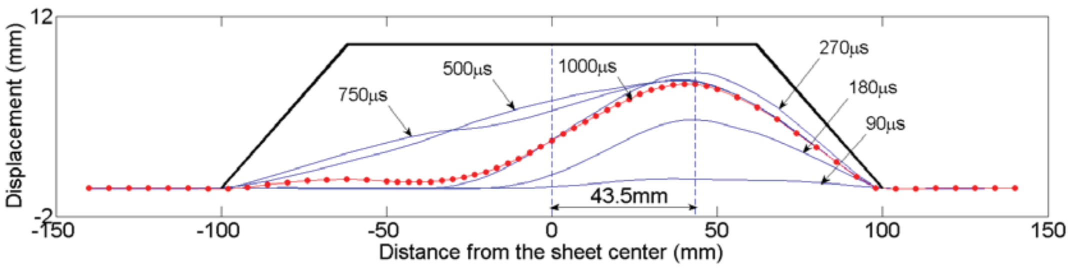
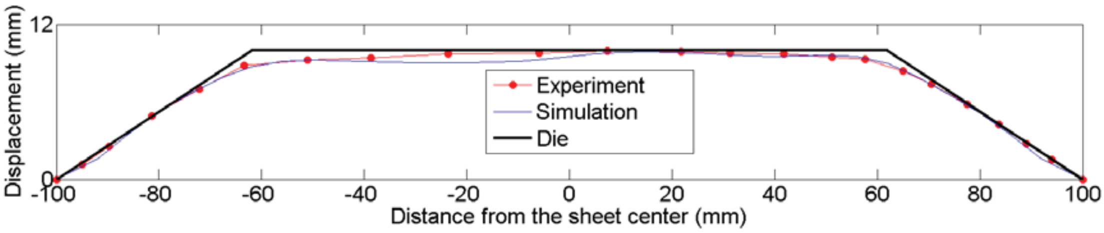


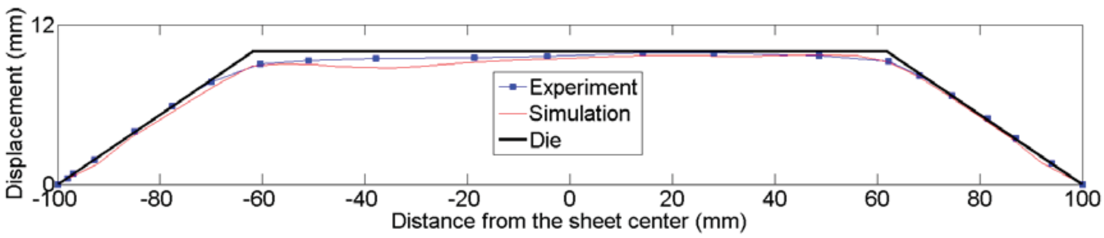

***Fig.13*** *Sheet profiles in path 1 in 2000V discharge voltage*

As shown in Fig.14, the experimental data are compared with the simulation data and good agreements between them are obtained. The sheet has good moldability with the die side surface in the experimental and simulation values. In addition, it can be seen that the calculated displacement is smaller than the experiment in the location from -45mm to 10mm in path 1 and from -55mm to 43mm in path 2. The probably reason is that the air resistance is ignored in the simulation process, which causes the sheet has a lager deformation speed than the experimental value and the bound effect is increased. In the location of -60mm and 60 mm from the sheet center in path 1 and path 2, the sheet don't stick onto the die bottom surface.

This shows the technological parameter, such as coil structure and the distance between the coil center and the sheet center play important influence in EMIF process.




(a)




(b)

***Fig.14*** *Simulation results along two paths (a) path 1; (b) path 2*

## 5. Conclusion

The following conclusions are drawn:

- The experiments shows: (1) The air resistance hinder and slow the deformation speed; (2) A higher discharge voltage will cause sheet impact with the die in a high speed and the bound effect appears, while the sheet has a good moldability with the die side surface. (3) Multi-times with varying value of discharge voltage can improve the sheet forming quality and reduce the bound effect.
- The EMIF technology is feasibly to produce a large part with small working coil and small discharge energy, which enhance the flexible forming process of EMF. How to improve the product accuracy is a task to be solved in the follow-up study.
- A new simulation method for EMIF is proposed. The simulation results are good agreement with the experimental values. The simulation method can also be used for more complex 3D forming system, which solves the bottleneck problem in numerical simulation of EMF.

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