Electromagnetically assisted sheet metal stamping with non-disposable foil coils

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Abstract: Coil in electromagnetic forming (EMF) process commonly requires high strength and long longevity to be robust enough to accommodate great input energy that makes the coil difficult and costly to be manufactured. However, foil coils, in most cases, utilized for part calibration, vaporized for shearing, welding and embossing are less consuming in both time and outlay, easier to be fabricated and replaced, but are mostly disposable. Therefore, the purpose of this paper is to study feasibility of utilizing non-disposable foil coils in EMF process via forming the part (150mm×150mm) with hyperbolic curve like cross-section feature with 1mm thickness AA 2524-T3 aluminum alloy sheet. Copper foil of 0.5mm, 1mm thickness, wrapped in polyimide insulation foil are used as coils in two steps of a quasi-static two-mould-closing pre-forming and EMF process. Besides, practical orthogonal tests are deployed to explore these coils’ forming performance and find the factors’ influential sequence to obtain appropriate process parameters. Results of loose coupling simulation with selected parameters, using ANSYS APDL macro and ABAQUS keywords will be presented and compared with formed components corresponding to simulation load steps. Eventually, formability of sheet component under conditions of diverse charging voltage, foil thickness, foil layers and number of loading repetition and longevity of these coils were experimentally investigated. And the study demonstrates that this technique can be used to improve sheet metal stamping process.

1. Introduction

Coils used in traditional electromagnetic forming (EMF) process are commonly demanded to be durable, with high strength and good insulation performance that coils could be too thick in the forming direction. Hence, these coils need to be fabricated by machining with blanks or bending with metal bars in most cases. Furthermore, these coils are generally wrapped with epoxy resin, not only for reinforcing their structural strength, but for insulation, which is one of key requirements in EMF process. For instance, failures of flat coil blocks of a simple single layer can be easily caused by breakdown of insulation layer, such as fracture of insulation block, telescoping effect and turn deformation due to insufficient insulation thickness [1]. Therefore, the whole process from conceiving to manufacturing is time-consuming, costly and inefficient, especially for coils in multi-layers.

The multi-layer coil plays a vital role in EMF process, as its producing induced current several times greater than coil with single layer, so the magnitude of produced Lorenz force could have a leap based on increased coil layers. However, multi-layer coil’s structural complexity and its fabrication cost increase along with the increase of coil layers. Accordingly, a multi-layer coil could be easily or even inevitably damaged in both insulation layer and conductive layer and have a short service life during EMF process as parts formed in such a high speed, high forming frequency and high peak
voltage. An extra cost of coil restoration and redundant coils for replacements thus could occupy a large proportion of total cost.

According to the illustration above, creating a non-disposable, low-cost, highly replaceable foil coil, whose multi-layers can be simply achieved by the superposition of single layer coils, is essential to be used in EMF process and thus becomes the main objective of this paper. Besides, these foil coils are suitable to be applied in electromagnetically assisted sheet metal stamping technic, which is a combined process of stamping and EMF, such as the use of inbuilt bar coil in specially redesigned punch [2-3].

So far, 0.64mm thick foil coils were used to form flat sheets to obtain their forming performance, which was evaluated by resulted radius of curvature. And an expressly designed foil coil of the same thickness was disposably used to eliminate wrinkles of the part, namely, used as part calibration [4].

The other uses of foil coils are shearing, collision welding, impulse forming and embossing via vaporizing foil actuators [5-8] and applications of these vaporized disposable foil actuators show that thin foil actuators can produce forming force no less, or even higher than force produced with traditional thick coils used in EMF process. Therefore, using foil coils in EMF process will have a bright future for its low cost, multi-function, and flexibility.

2. Experiment methods and procedure

2.1. Material
The material of target component is aluminum 2524-T3, which has been widely used in vehicle and aerospace production. And the static property of this material is shown in Table 1.

| Property          | Value       |
|-------------------|-------------|
| Density (t/mm³)   | 2.78×10⁻⁹  |
| Elasticity modulus (MPa) | 73100 |
| Poisson’s ratio   | 0.33        |
| Tensile strength (MPa) | 483  |
| Yield strength (MPa) | 345  |
| Elongation (%)    | 18%         |
| Resistivity (Ω·m) | 5.82×10⁻⁸  |

Besides, an exploration test was carried out to decide the sheet thickness to use. Fig. 1 was the test result. During the test, two types of part with two different thickness were formed under the conditions of 8kV peak voltage, 3 layers of 0.5mm thick foil coil and hitting times of 20 and found no obvious changes for 2mm thick part, but the another shows a significant positive effect, especially on the first bending radius. Therefore, square shape metal plates of 150mm×150mm cut from 1mm thick 2524-T3 aluminum sheets have been prepared for practical tests.

![Figure 1](image1.png)

Figure 1. Comparison among target shape and formed metal sheets from exploration tests.

2.2. Equipment and foil coils
The equipment consists of the punch and die, clamps, the mechanical structure and workbench.

Additionally, the practical forming steps consist of a quasi-static two-mould-closing pre-forming and an EMF process. The first step is illustrated in Fig. 2a and Fig. 2b below. Foil coils and metal plate are pre-formed at center position of moulds and locked by the mechanical structure and two G shape jigs. Then, epoxy-resin-made fixture tools are used to clamp electrodes and foil coil tightly to acquire an effective connection. After the work above, EMF process then can be launched.
Figure 2. a) Diagram of the equipment. b) The practical equipment used for electromagnetically assisted stamping process. c) Design and size of the foil coil wrapped in polyimide.

Shape and size of the foil coil is shown in Fig. 2c above and the coils in both 0.5mm and 1mm thickness are prepared with three layers. These foil coils are wrapped with 0.12mm thick polyimide, which not only guarantees insulation, but strengthens themselves and prolongs their service lifetime with lower cost and less pollution comparing with epoxy resin used in producing traditional EMF coils. Besides, the coil is designed via referring to the one embedded in punch used for shape calibration [9], but is designed wider to cover most areas of metal sheet to avoid wavy profile phenomena and placed on the surface of mould rather than inbuilt in it [3] to reduce the cost of redesigning and manufacturing moulds that are still required in other forming processes.

2.3. Experimental methods
For acquiring appropriate process parameters, a practical orthogonal test shown in Table 2 was carried out to explore the foil coils’ forming performance and find the influential sequence of these factors as well as measure the currents’ value for the need of simulation. And each test was conducted twice to ensure reliability of the data.

|   | A: Peak voltage (kV) | B: Coil thickness (mm) | A×B | C: Number of layers | A×C | B×C | D: Combined hitting times |
|---|----------------------|------------------------|-----|---------------------|-----|-----|--------------------------|
| 1 | 5                    | 0.5                    | 1   | 1                   | 1   | 1   | 10+16                    |
| 2 | 5                    | 0.5                    | 1   | 3                   | 2   | 2   | 14+22                    |
| 3 | 5                    | 1                      | 2   | 1                   | 1   | 2   | 14+22                    |
| 4 | 5                    | 1                      | 2   | 3                   | 2   | 1   | 10+16                    |
| 5 | 8                    | 0.5                    | 2   | 1                   | 2   | 1   | 14+22                    |
| 6 | 8                    | 0.5                    | 2   | 3                   | 1   | 2   | 10+16                    |
| 7 | 8                    | 1                      | 1   | 1                   | 2   | 1   | 10+16                    |
| 8 | 8                    | 1                      | 1   | 3                   | 1   | 1   | 14+22                    |

The parameters in the table above were selected for a proper reason. Peak voltages of 5kV (input energy: 3.1kJ) and 8kV (input energy: 8.0kJ) are the highest and the lowest stable peak voltage in this EMF system and thus levels of factor A is determined.

Coil thickness is determined as 0.5mm and 1mm because coils with excessively thin thickness could be damaged and even instantaneously destroyed or become disposable foil actuators used for EMF vaporizing process during inputting tremendous amounts of energy. Moreover, thick foil coil, such as 2mm thick coil, may not sufficiently deform in pre-forming process that it could not completely fit in moulds causing undesirable results due to the interspace.

The maximal value of coil layer is set to three, because a reverse pull appeared on local of the fourth layer of the coil according to [10] and results achieved with more than three layers could be undesirable due to the opposite effect brought by redundant layers.
The variable of combined hitting times is composed of an overall and a partial coverage hitting because the preliminary electromagnetic finite element simulation of one layer of foil coil under peak voltage of 5kV showed the nodal force distribution on forming direction that generated high stress area should be sufficiently used. As shown in Fig. 3a, nodal force on top of the coil is greater than on other regions. Therefore, coil was moved down 35mm shown in Fig. 3b to take advantage of the coil’s well-distributed and strong force region to form the part’s curved region, namely used as calibration.

![Figure 3](image)

**Figure 3.** a) Nodal force distribution on forming direction. b) Explication of an overall coverage and a partial coverage with coils.

The values of combined hitting times used in the orthogonal test above were determined by two experiments under conditions shown in Fig. 4. And hitting times were determined after radii of formed parts were approximately achieved with the criteria of 22.5mm for R1 and 30mm for R2, namely a deviation of 50% for both radii. The result in Fig. 4 shows that part formed with 0.5mm thick foil coils is much closer to the target with less hitting times comparing with another one due to the greater current density produced within the thin coils.

![Figure 4](image)

**Figure 4.** Achieved shape in test A and B to determine the value of combined hitting times.

3. Result and discussion

3.1. Orthogonal test result processing

The two influential sequences for radius R1 and R2, which were the references for adjusting forming parameters were determined by sorting sequence Range1 and Range2. The outcome of the orthogonal test above was processed in Table 3 and it shows that R1 is most affected by the interaction of coil thickness and coil layers and less affected by the interaction of peak voltage and coil layers. However, these two factors have an opposite effect on R2.

Considering forming both R1 and R2 features with as few hitting times as possible and factors’ cross effects, preliminary parameters for the following simulations are set as A2 B1 C1, which are peak voltage of 8kV, 1 layer of 0.5 mm foil coil for forming R1 and A2 B1 C2, which remains the same except using 3 layers of foil coil for forming R2.
3.2. Simulation to define hitting times and experimental result

A loose coupling simulation method consisting of an electromagnetic analysis and a structural analysis has been adopted to forecast elastic and plastic deformation of metal sheet according to the measured time-current curve under designated parameters.

The first section of simulation is electromagnetic analysis completed with ANSYS APDL macro, which can calculate cases easily with time-current data and output node number and nodal force data to created files with designated output time interval.

The second section is structural analysis, including steps of pre-forming process with a dynamic explicit step with punch descending speed of 3.9mm/s, following steps of applied nodal forces obtained in the first section and a general static step with predefined field to simulate springback. This section is achieved with an inbuilt ABAQUS macro called keywords that can be automatically recognized to run simulations.

Additionally, meshes used in these two simulations were generated with Hypermesh software that nodes have been redefined with a certain node number sequence for applying nodal loads and post-process. The whole simulation process thus can be simplified as outputting loads, invoking load files, calculating steps, post processing and rerunning cases with adjusted parameters.

Because parameters except combined hitting times were predefined in previous chapter, structural simulation results have been checked every time increasing two or more hitting steps to acquire a proper range of hitting times. Eventually 22 and 34 were determined as the first and the second value of combined hitting times when these two radii were formed as shown in Fig. 5 below that R1 and R2 were measured as 14.8mm and 20.6mm. Besides, the high stress region was concentrated upon the designated area and this was in agreement with expectation.

![Simulation result and the comparison between target shape and scanned result.](image)

According to Fig. 5 above, formed shape was digitalized with a 3D laser scanner to make a better comparison between target shape and experimental result. The result revealed that bottom area of the part was gradually deviated from target shape due to R2 being incompletely formed. However, the deviation on top area of the part is because this area was excessively hit by the high stress region.

### Table 3. Orthogonal test result processing.

| A: Peak voltage (kV) | B: Coil thickness (mm) | A×B | C: Number of layers | A×C | B×C | D: Combined hitting times |
|----------------------|------------------------|-----|---------------------|-----|-----|---------------------------|
| K1(R1)              | 101.2                  | 87.6| 88.1                | 83  | 84.1| 95.5                      | 99.8                      |
| K2(R1)              | 83.1                   | 96.2| 96.2                | 101.3| 100.2| 88.8                      | 84.5                      |
| Range1              |                        |     |                     |     |     |                           |                          |
| K1(R2)              | 139.5                  | 122.9| 123.9              | 130.1| 126.3| 136.1                      | 135.7                     |
| K2(R2)              | 112.4                  | 129 | 128                | 121.8| 125.6| 115.8                      | 116.2                     |
| Range2              | 27.1                   | 6.1 | 4.1                | 8.3 | 0.7 | 20.3                      | 19.5                      |

Influential sequence:
- For R1: B×C, A×B, B, D, A×C, A, C
- For R2: A×C, A×B, B, C, D, B×C, A
4. Conclusion
This work demonstrates that forming small curved feature component using these economical, fleetly manufactured, highly replaceable, non-disposable foil coils in EMF process is feasible. And the final experiment shows that both R1 and R2 features have been mostly achieved with parameters referring to the two influential sequences and simulation result. Therefore, forming parameters as higher voltage with three layers of thinner foil coils could be suitable for using foil coils in EMF process.

Longevity of the foil coils has been investigated via the total hitting times accumulated from the beginning up to now, which are over 250 times for 0.5mm thick foil coil and over 160 times for 1mm thick foil coil. And all foil coils are still usable and undamaged, which is far beyond expectation. However, foil coil’s low energy efficiency reveals that foil coils are probably suitable for small scale production of non-complex part or part calibration. Furthermore, forming a larger region of the moulds with foil coils will be further investigated.

References
[1] V. Psyk, D. Risch, B.L. Kinsey, A.E. Tekkaya and M. Kleiner 2011 Electromagnetic forming— A review J. Materials Processing Technology 211 806–8
[2] M.K. Choi, H. Huh and N. Park 2017 Process design of combined deep drawing and electromagnetic sharp edge forming of DP980 steel sheet J. Materials Processing Technology 244 334–41
[3] Jianhui Shang and Glenn Daehn 2011 Electromagnetically assisted sheet metal stamping J. Materials Processing Technology 211 869–71
[4] Steven Woodward, Christian Weddeling, Glenn Daehn, Verena Psyk, Bill Carson and A. Erman Tekkaya 2011 Production of low-volume aviation components using disposable electromagnetic actuators J. Materials Processing Technology 211 887–94
[5] Anupam Vivek, John D. DeFouw and Glenn S. Daehn 2014 Dynamic compaction of titanium powder by vaporizing foil actuator assisted shearing J. Powder Technology 254 182
[6] Marlon Hahn, Christian Weddeling, Geoffrey Taber, Anupam Vivek, Glenn S. Daehn and A. Erman Tekkaya 2016 Vaporizing foil actuator welding as a competing technology to magnetic pulse welding J. Materials Processing Technology 230 9–11
[7] A. Vivek, S.R. Hansen, B.C. Liu, and Glenn S. Daehn 2013 Vaporizing foil actuator: A tool for collision welding J. Materials Processing Technology 213 2306–7
[8] A. Vivek, R.C. Brune, S.R. Hansen and G.S. Daehn 2014. Vaporizing foil actuator used for impulse forming and embossing of titanium and aluminum alloys J. Materials Processing Technology 214 867–9
[9] E. Iriondo, J.L. Alcaraz G.S. Daehn, M.A. Gutiérrez and P. Jimbert 2013 Shape calibration of high strength metal sheets by electromagnetic forming J. Manufacturing Processes 15 185–92
[10] Wenyong Luo, Liang Huang, Jianjun Li, Xianlong Liu and Zhiqiang Wang 2014 A novel multi-layer coil for a large and thick-walled component by electromagnetic forming J. Materials Processing Technology 214 2814–5

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