A Dual-Coil Method for Electromagnetic Attraction Forming of Sheet Metals

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ABSTRACT
Electromagnetic forming is a novel technology in which a coil is used to generate a pulsed Lorentz force for shaping sheet metal pieces. However, the Lorentz force between the coil and the sheet metal is generally repulsive due to the Lenz’s Law, which limits the practical application of this technology. To break this bottleneck, a dual-coil method is proposed to generate attractive Lorentz force, which is then used to form sheet metals. The theoretical principle of this method is presented, and an infinite element model is established to simulate the forming effect. The simulation results show that an A1060-O plate with a diameter of 140 mm and thickness of 1 mm can be attractively shaped under this method. The maximum axial displacement of the plate reaches 2.74 mm. Unfortunately, a dent exists in this situation. Further analysis indicates that this dent can be eliminated by increasing the inner and outer diameters of the coils. Further, it is found that when the capacitance value of the long pulse-width discharge circuit is set to 5.6 mF and the initial discharge voltage is set to 10.690 kV, the sheet metal attains the best shape.

INDEX TERMS
Electromagnetic forming, optimization, numerical simulation, sheet metal, dual-coil.

I. INTRODUCTION
Owing to its unique advantages of high-speed plastic deformation and non-contact ability and the high-plastic effect, electromagnetic forming (EMF) technology has garnered considerable attention in shaping tubes and sheet metals. EMF of sheet metals and tube fittings has been applied in electromagnetic bulging [1]–[4], electromagnetic welding [5], electromagnetic compression [6], [7], electromagnetic stamping [8], [9], electromagnetic incremental forming [10], etc.

However, most of the existing studies on EMF are based on electromagnetic repulsive force, and very few studies have focused on electromagnetic attraction. This is mainly because the generation of electromagnetic attraction is more challenging. As shown in Fig.1, a pulsed current is applied to a coil to generate a strong pulsed magnetic field in the forming area. At the same time, the pulsed magnetic field induces an eddy current in the workpiece, whose direction and strength can be determined by the Lenz’s Law.

In conventional EMF process, the electromagnetic force on the workpiece is mainly repulsive. According to the existing literature, generation of dual-frequency discharge current is the primary method for realizing electromagnetic attraction in EMF with wide applicability range [11]. Based on this method, Cao et al. [12] achieved an attractive force using a single coil driven by two pulsed power supplies and a timing control system. They conducted experiments on AA1060-O sheet metal pieces. Further, Xiong et al. [13] applied this method to the bulging process of small-size tube fittings for shaping the fittings. However, it must be pointed out that the dual-frequency discharge current method can deteriorate the insulation and durability of the coil. For example, when the coil structure and the number of turns are fixed, a high voltage is needed to generate a large current and a strong magnetic field for realizing a strong attraction on the workpiece. However, the coil can also be subjected to a large stress (usually several hundred MPa), which is far beyond the yield strength of a copper coil. Further, the coil usually exhibits a multi-layer, multi-turn structure, which makes it more susceptible to damage and eventually leads to an unstable structure. To resolve this issue, Xiong et al. [14] and Ouyang et al. [15] improved...
the single-coil system to a dual-coil system, which has been successfully used in the flanging and the bulging of aluminum alloy tube fittings.

However, compared to the rapid progress in tube fittings, the dual-coil method for electromagnetic attraction forming of sheet metals has not evolved yet. This is primarily attributed to the fact that the sheet metals are mainly subjected to an axial force but the tubes are subjected to a radial force, which are totally different forces and the former is more difficult to control. To break this bottleneck, we have proposed a dual-coil method to generate an attractive Lorentz force for forming sheet metals. The theoretical principle of this method is presented and an infinite element model is established to simulate the EMF process.

II. PRINCIPLE AND DESIGN

A. BASIC PRINCIPLE OF ELECTROMAGNETIC ATTRACTIVE FORMING OF SHEET METAL

Sheet metal forming technology based on electromagnetic repulsive force is widely used in several applications such as deep forming of sheet metals assisted by radial force [16], deep forming of large sheet metals under axially movable coils [17], and optimization of forming precision of sheet metals [18], [19]. These studies indicated that when a pulsed current is circulated in the coil, a time-varying magnetic field with constant direction and varying strength is generated. According to the Lenz’s law, when the coil current is on the rising edge, an eddy current is induced in the workpiece in opposite direction.

Moreover, according to the Lorentz force law, the workpiece is subjected to a downward repulsive electromagnetic force, as shown in Fig.1, and when this force is large enough, the workpiece suffers a downward plastic deformation. Therefore, the electromagnetic force density in the workpiece can be expressed as follows:

\[ f_m = J_e \times B \]  

where, \( J_e \) is the induced eddy current density in the workpiece and \( B \) is the magnetic induction density in the forming area. Moreover, if the coil and plate are both axisymmetric, \( J_e \) has only one annular component \( J_{e-phi} \). Thus, electromagnetic force \( f_m \) has a radial component \( f_{mr} \) and an axial component \( f_{mz} \). Therefore, the Lorentz force acting on the workpiece can be expressed as:

\[ f_{mr} = J_{e-phi} \times B_z \]  
\[ f_{mz} = -J_{e-phi} \times B_r \]  

where \( B_z \) and \( B_r \) represent the axial and radial components of magnetic flux density \( B \), respectively. Here, \( f_{mz} \) is mainly used to represent axial electromagnetic force in the traditional EMF technology, and the negative sign in Eq. (3) indicates repulsive force.

Generally, it is very difficult to change the direction of force because the eddy current and magnetic field are coupled. A feasible method to transform the electromagnetic force from repulsive to attractive is to decouple the eddy current and the magnetic field [12], [13]. It can be deduced from Eq. (3) that if either one of the magnetic flux density \( B_r \) and the induced eddy current density \( J_{e-phi} \) is fixed, and the other one is changed in direction, then the repulsive electromagnetic force can transform into attractive force. However, this is nearly impossible to realize in the traditional method because \( B_r \) and \( J_{e-phi} \) are coupled.

Therefore, this decoupling can be achieved by the following strategies: I) varying the eddy current (both direction and magnitude); II) varying the magnetic field (the direction of the synthetic magnetic field is reversed). For changing the eddy current and the magnetic field, two power supplies are required to generate current pulses with long and short pulse widths, respectively.

Based on the above analysis, in the time interval of \([0, t_1]\), the current pulse with short pulse width is not applied, as shown in the Fig.2. Consequently, the direction of eddy current in the plate does not change, and the plate is mainly subjected to electromagnetic repulsive force. When the
current pulse with short pulse width is applied, the direction of eddy current in the workpiece is reversed (the value is relatively large), but the direction of magnetic field is not changed. Therefore, it can be inferred from Eq. (3) that an attractive force is generated between the coil and the workpiece. Therefore, the axial electromagnetic force of the workpiece can be represented as:

$$\begin{align*}
    f_{mc} &= \begin{cases} 
    f_R = -J_{e-\phi L} \times B_{r-L}, & t < t_1 \\
    f_A = -(J_{e-\phi L} + J_{e-\phi S}) \times (B_{r-S} + B_{r-L}), & t > t_1
    \end{cases}
\end{align*}$$

Here, $B_{r-S}$ and $B_{r-L}$ represent the radial components of the magnetic flux density generated by the current pulses in the coil with long pulse width (low frequency) and short pulse width (high frequency), respectively. Further, $J_{e-\phi L}$ and $J_{e-\phi S}$ are the annular eddy current density in the workpiece induced by the current pulses with long and short pulse widths, respectively. Furthermore, it may be noted that the direction of eddy current in the workpiece is positive in the clockwise direction. Thus, $f_R$ and $f_A$ indicate repulsive and attractive force on the workpiece, respectively.

B. DESIGN OF ATTRACTIVE FORMING OF SHEET METALS WITH DUAL-COIL SYSTEM

For the complex structure shown in Fig.3 (a), the decoupling of eddy current and magnetic field cannot be achieved by simply increasing or decreasing the value of the current. This is mainly because when the current in the coil changes, the magnetic field and the induced eddy current also vary, which leads to uncontrollable factors in multivariate process control. To this end, we have proposed an electromagnetic attraction method for forming sheet metals based on a dual-coil and dual-power supply system, as shown in Fig.3(b). Further, the strategy II (changing the magnetic field) is adopted to analyze this attraction forming process.

In Fig.3, $C_S$, $R_S$, $L_S$, $R_{DS}$, and $D_S$ are the capacitance, line resistance, line inductance, continuation resistance, and the fly-wheel diode of the long pulse-width system, respectively, while $C_f$, $R_f$, $L_f$, $R_{df}$, and $D_f$ are the corresponding parameters for the short pulse-width system.

In addition, as shown in Fig.4, the current pulse with long pulse width in the outer coil is mainly used to generate a large radial magnetic field $B_r$ in the forming area, while the pulse current with short pulse width in the inner coil is primarily used to induce a large eddy current $J_e$ in the sheet metal. Moreover, the amplitude of the current pulse with long pulse width is larger than that of the current pulse with short pulse width, and the number of turns in the outer coil is much higher than that in the inner coil. Further, the frequency of current pulse with short pulse width is much higher than that of current pulse with long pulse width (i.e., the capacitance of the outer coil in the discharge system is much higher than that of the inner coil). It can be seen from Fig.4 that the direction of current flow in the inner coil is opposite to that in the outer coil, and to realize an effective control on the magnetic field strength in the forming area and the eddy current in the sheet metal (direction and size distribution), the current must be circulated in the inner coil when the current in the outer coil reaches its peak value.

Further, the magnetic field intensity is primarily adjusted by varying the capacitance value in the long pulse-width
circuit (this is because when the capacitance value changes, the synthetic magnetic field is changed, while the eddy current density in the sheet metal remains nearly unaffected). Consequently, decoupling between magnetic field and eddy current is realized, as shown in Fig. 5. Moreover, the magnetic field in the forming area and the induced eddy current in the sheet metal generated by the inner and outer coils are shown in Fig. 5 (a) and (b), respectively.

III. SIMULATION AND ANALYSIS
A. TWO-DIMENSIONAL AXISYMMETRIC MODEL FOR THE DUAL-COIL SYSTEM

To analyze the dynamics of the attraction forming process of sheet metal, we established a finite element model for dual-coil sheet metal. This following four models are included in this simulation: global ordinary differential equations (ODEs), magnetic fields, solid mechanics, and moving mesh [20]. Moreover, based on earlier studies [12]–[15], the three-dimensional (3D) model can be simplified to a two-dimensional (2D) axisymmetric model due to the symmetric nature of the coil and plate structure. Further, the precision of this model meets the engineering requirements.

Therefore, based on the above analysis, a simplified simulation model of plate forming under a 2D axisymmetric dual-coil system and sheet metals was established by COMSOL Multiphysics software.

As shown in Fig. 6, the specific parameters of this simulation model are set as follows:

(1) Geometric parameters for the inner coil: There are 4 layers, 3 turns for each layer, and 12 turns in total. The wire material is pure copper, and the section size is $1 \times 4$ mm$^2$. The inner and outer diameters of the coil are 15 mm and 20.5 mm, respectively.

(2) Geometric parameters of the outer coil: There are 9 layers, 5 turns for each layer, and 45 turns in total. The wire material is pure copper, and the size of coil section is $1 \times 4$ mm$^2$. The inner and outer diameters of the coil are 30 mm and 43 mm, respectively.

(3) Geometric parameters of the sheet metal: The workpiece used is an A1060–O sheet metal with a diameter of 70 mm and thickness of 1 mm.

(4) Positional relationship of coils and sheet metal: The inner and outer coils are coaxially arranged on the same horizontal plane. The plate is coaxial with the coil and is located directly below the coil (the distance between the plate and the coil is 8 mm). In addition, both the inner and the outer coils are layer reinforced with Zylon fibers (Zylon reinforcement layer is 0.5 mm thick per turn). The material parameters for the coils, plate, and Zylon are shown in Table 1.

To accurately analyze the dynamics of sheet forming process, the model, plate, internal and external coils, and Zylon fiber of the reinforcement coil are divided using a quadrilateral mesh with a maximum cell size of 0.5 mm, as shown in Fig. 6 (b). Further, the air region is divided with a triangular mesh, where the maximum cell size is 1 mm.
During the EMF process, the workpiece is formed at a high speed, and the dynamic changes occur in extremely short time. Therefore, the stress-strain relationship [21] of the material has a strong effect on the forming of the plate. Due to the high stress and strain in EMF, the final result of forming process is considerably affected. Therefore, the Cowper-Symonds constitutive model was adopted to analyze the forming of the plate. The specific model is described as:

\[
\sigma_{CS} = \left[1 + \left(\frac{\varepsilon_{pe}}{C_s}\right)^m\right] \cdot \sigma_q
\]

(5)

where \(\sigma_q\) and \(\varepsilon_{pe}\) are quasi-static stress (MPa) and the plastic strain rate (s\(^{-1}\)) respectively. \(C_s\) and \(m\) are 6500 s\(^{-1}\) and 0.25 for aluminum alloy.

The pulse circuit consists of two sets of power supply devices, which are fed into the inner and outer coils to generate the pulsed magnetic field, respectively. Moreover, the long-pulse power supply (with large capacitor) is mainly used to generate the magnetic flux density \(B\), while the short-pulse power supply (with small capacitor) is used to generate the reverse eddy current density \(J_{e-ph}\) in the sheet metal. The structure of the dual power supply discharge circuit is shown in Fig.3 (b), and the detailed circuit parameters are shown in Table 2. Firstly, the electric energy stored in the capacitors \((C_s\) and \(C_f\)) is transmitted to the driving coil as soon as the light-activated thyristor switch is closed, and an RLC series discharge circuit containing a secondary circuit is then formed. Finally, the coil is energized by timing control.

### B. SIMULATION RESULTS

1) COIL CURRENT, EDDY CURRENT, AND MAGNETIC FIELD

To further clarify the dynamics of EMF of sheet metal, the initial discharge voltages of the inner and outer coils were set to 6.8 kV and 10 kV, respectively. Fig.7 shows the waveforms of current pulses with long and short pulse widths. It can be seen that the current pulse with short pulse width is triggered at 2.3 ms (i.e., the moment when the current pulse with long pulse width in the outer coil reaches its maxima), and within a very short time of 0.06 ms, the short pulse-width waveform reaches its peak value of 17.720 kA.

![Figure 7. Current waveforms for the inner and outer coil.](image)

Fig.8 and 9 show the direction and intensity distribution of radial magnetic field as well as the direction and density distribution of eddy current in the forming area when the long and short pulse-width systems are implemented. It is evident that after the short pulse-width current pulse is circulated in the inner coil (2.3 ms later), the direction of eddy current in the central region of the sheet metal is immediately reversed, and the maximum eddy current density reaches 2.42 × 10^9 A/m². This is mainly because the capacitance value of the discharge circuit of the inner coil can adjust the steepness of the current waveform and consequently the induced eddy current density in the sheet metal is modified.
Therefore, to induce a high eddy current density $J_{\text{phi}}$ in the sheet metal, the capacitance value of the discharge circuit of the inner coil is set as 120 $\mu$F. Moreover, as shown in Fig.10, the amplitude of the composite magnetic field exhibits a minor change, and its direction remains unchanged, which does not affect the final forming of the sheet metals. Therefore, it can be proved by the simulation cloud map that when the circuit parameters (e.g., capacitance value of long pulse-width circuit) are adjusted properly, the forming area on the plate can be more attractive. However, this results in confinement of the attraction forming area (the area of attraction) to the region in which the direction of eddy current is reversed in the sheet metal.

2) SHEET METAL DEFORMATION

Here, the point A (the midpoint) on the sheet metal in Fig.6 is selected for analyzing its axial displacement. Based on Fig.7-11, there are three stages in the EMF process of sheet metal:

1. 1$^{\text{st}}$ stage: When the short pulse-width current in the inner coil is not applied, magnetic field is mainly generated by the long pulse-width current pulse in the outer coil and the eddy current in the plate causes the generation of downward repulsive electromagnetic force.

2. 2$^{\text{nd}}$ stage: When the short pulse-width current pulse is applied, the eddy current in the middle area of the sheet metal is reversed (the eddy current density is relatively larger), and the direction of the composite magnetic field in the forming area changes.
area remains unchanged. In this case, the sheet metal is subjected to an upward attractive electromagnetic force.

3rd stage: Finally, the attraction forming is realized, and the maximum axial displacement at point A reaches 2.35 mm.

According to the previous analysis, the capacitance value determines the pulse width and rise time of the current pulse. Therefore, we employed the discharge energy of the long pulse-width circuit for further analysis. The discharge energy $W_{cs}$ of the long pulse-width circuit is set to a fixed value of 0.32 MJ, and the capacitance value and the initial discharge voltage value of the long pulse-width circuit are varied to analyze the transient process of the plate's attraction forming.

As shown in Fig.6 (a), the outer region of the sheet metal in the finite element model is set to a fixed state. Therefore, starting from the midpoint of the sheet metal (at 0 mm), 26 points are sequentially selected at 1 mm distance along the radial axis (cylindrical coordinate system). When the energy of long pulse and wide discharge is constant, the axial electromagnetic force at each point is calculated to examine the forming process of the sheet metal. The magnitude of the axial electromagnetic force density at different points on the plate of the short pulse current in different models and the relationship between the axial displacement of the point A and time are shown in Fig.12 (a) and (b), respectively.

It is evident from Fig.12 (a) that when the capacitance value is 5.6 mF, the axial electromagnetic force density at each point of the plate is larger than zero (attractive force region). The final axial displacement at point A on the plate is greater than zero except when the capacitance value is 4.8 mF, as shown in Fig.12 (b) and Table 3. Comparing the results of the models with different parameter values, it can be inferred that when the discharge energy of the long pulse-width circuit is constant, there is an optimal set of voltage and capacitance values, which facilitate the best attraction forming of the sheet metal. This implies that when the capacitance and voltage value are 5.6 mF and 10.690 kV, respectively, the maximum axial displacement at point A of the sheet metal is 2.57 mm.

In the forming region of the sheet metal, both anti-clockwise eddies $J_{e-\phi F}$ (only distributed in the middle area of the sheet metal) and clockwise eddies $J_{e-\phi S}$ exist. However, in the plate area where the vortices coincide in different directions (away from the inner coil and close to the outer coil), the eddy current density $J_{e-phS}$ is relatively large,
which leads to the formation of defect area (the maximum axial displacement of the defect area on the sheet metal is $-0.09\text{ mm}$), as shown in Fig.13.

**IV. OPTIMIZATION**

In the proposed model, due to the size of the inner coil, when the short pulse-width current pulse is applied, the anti-clockwise eddy current induced in the plate is only distributed in the circular area with a diameter of 59 mm. This results in stronger electromagnetic attraction over an extremely limited region of the plate (which matches the outer diameter of the inner coil). This is mainly attributed to the fact that the anti-clockwise and clockwise eddy currents induced by the inner and outer coils, respectively, are superimposed in the plate forming area. This leads to the generation of anti-clockwise synthetic eddies in the middle region of the plate. Therefore, under the action of the composite magnetic field, a stronger attraction is generated on the plate. However, since the direction of the induced eddy current is clockwise, the sheet metal is subjected to a downward repulsive electromagnetic force, which causes the formation of defect area on the sheet metal.

Therefore, due to the existence of defects in the forming area of sheet metal, to obtain a better forming effect, we focus on the reduction or elimination of the influence of the eddy current competition in the forming area of sheet metal by changing the inner diameter of the coil. Consequently, as shown in Fig.14, coil models of different sizes with a radius of 15-25 mm are established to explore the relationship between coil diameter and defect area on the plate.

According to the analysis in the previous section, when the capacitance value of the discharge circuit of the outer coil is 5.6 mF and the initial voltage is 10.690 kV, the axial displacement of the sheet metal reaches its maximum. Therefore, these parameters are selected to rectify the defect area (dent area) on the sheet metal.
FIGURE 16. Ratio of effective area length to dent area length when only the inner diameter of inner coil and outer coil is changed. Here, \( L_{\text{effective}} \) is the effective length of the forming area and \( L_{\text{dent}} \) is the length of the dent area.

Furthermore, to verify the relationship between the defect area and the coil diameter in the eddy current competition region, five coil models with different diameters were established. As shown in Fig.14, the inner diameters of the inner coil and the outer coil in these models are 30, 35, 40, 45, and 50 mm, and the distance between the inner and outer coils remains unchanged (9.5 mm).

When the diameter of the inner and outer coils changes, the final forming effect of the sheet metal and the ratio of the length of the forming area \( L_{\text{effective}} \) to the length of the defect area \( L_{\text{dent}} \) are shown in Fig.15 and 16, respectively. It is clear from these figures that when the inner diameter of the coil increases, the size of the defect area on the plate changes. Moreover, when the inner diameter of the coil increases to 50/80 mm (Case 5), the sheet exhibits a downward forming effect, which is not desirable. When the inner diameter of the coil is 40/70 mm (Case 3, i.e., the inner radius is increased by 5 mm), the ratio of the effective forming length \( L_{\text{effective}} \) to the dent length \( L_{\text{dent}} \) on the plate is close to 50, and the maximum displacement of the dent area on the plate is minimum.

Therefore, according to the above analysis, when the inner diameters of the inner and the outer coils are increased by 10 mm, the forming effect of the sheet is optimal. Consequently, the area in which the anti-clockwise eddy current induced in the plate is increased, and the attractive electromagnetic force required for the forming of the sheet metal is also increased.

In the optimized model (Fig.17), the distribution area of the induced anti-clockwise eddy current in the sheet metal increases, while that of the composite magnetic field in the metal plate is small. Therefore, the corresponding defect (dent) area of the sheet metal is subjected to a stronger attractive electromagnetic force. Finally, the cloud diagram of plate’s axial displacement distribution in the forming region of the sheet metal (Case 3) is obtained, which is shown in Fig.15. It is clear that under this optimization model, the maximum axial displacement in the sheet metal increases to 2.74 mm, and that in the dent area is 0.01 mm, which is only 1% of the thickness of the sheet metal, thereby satisfying the requirements for accuracy. Therefore, it can be inferred that in the optimized model, the dent area on the sheet metal is adjusted well.

V. CONCLUSION

We proposed a dual-coil method to generate attractive Lorentz force for forming sheet metals. By adjusting the capacitance value of the circuit, the mutual decoupling of induced eddy current and the magnetic field was realized, and the attraction forming of sheet metals was achieved.

The simulation results showed that for \( C_S = 5.6 \text{ mF} \) and \( U_S = 10.690 \text{ kV} \), the plate attained the best forming effect with the maximum axial displacement of 2.57 mm. However, a dent area appeared on the plate. Furthermore, by increasing the inner diameter of the inner and outer coils, the maximum axial displacement of the dent area on the sheet metal was effectively reduced to 0.01 mm, which was only 1% of the thickness of the plate.

These results validate the feasibility and capability of this dual-coil method. Further, the proposed method can boost the practical applications of attraction EMF technology.

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