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Study of a Topology for Plate Electromagnetic Forming Based on Inner Reverse and Outer Positive Double Coil Loading

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ABSTRACT While electromagnetic forming is widely used for aluminum alloy materials, the non-uniformity of plate radial deformation is still a key issue that restricts the wide development of this technology. This article presents a new electromagnetic-forming topology. The proposed topology comprises outer ring double-coil plates along with an inner loop driving coil of a small number of turns whose geometrical parameters are optimized to adjust the induced eddy current of the plate. Numerical simulation results show that the presence of an inner ring driving coil shapes the magnetic field in a manner that the radial electromagnetic force is concentrated close to the edge of the die which affects the center of the plate. With optimum design for the geometrical parameters of the proposed inner ring driving coil, the electromagnetic force distribution can be adjusted over the plate, resulting in an improved plate deformation with an increase in the maximum uniform deformation area from 24mm to 65mm. Results also show that the proposed inner and outer ring double coil loading method possesses superior advantages over the traditional flat spiral coil loading method.

INDEX TERMS Electromagnetic forming, double Coil, Lorentz force, plate deformation.

I. INTRODUCTION

With the increased trend of employing lightweight, high-strength and low-density materials in various industrial applications, forming technology has been given much attention [1]–[3]. The conventional quasi-static stamping process results in poor formability of the aluminum alloy sheet, especially when the drawing ratio increases [4], [5]. Electromagnetic forming (EMF) is based on using pulsed electromagnetic-force to realize the processing of a metal plate [6]–[8]. Compared with conventional mechanical processing, electromagnetic forming can improve materials deformation performance and enhance its forming margin by 5-10 times due to its high strain rate (10^3-$10^5 s^{-1}$) [9]–[11]. At the same time, electromagnetic forming exhibits noncontact electromagnetic force which facilitates improved surface quality of the formed plate [12]–[14].

Electromagnetic forming is categorized into pipe electromagnetic forming and plate electromagnetic forming [15], [16]. Compared with the minimum constraint at the center of the plate, the bulging is difficult to control. The constraints of the pipe fittings are almost the same and the forming effect can be better controlled, so it is more widely used in industry [17]. However, in the free bulging of the plate, due to the small constraint at the center of the plate and the uneven distribution of the axial electromagnetic force generated by the traditional flat coil, this limits the application of plate processing technology [18], [19]. In [20] a new type of coil structure is designed to perform local electromagnetic force loading. Reported results show that by the use of a locally loaded coil, the electromagnetic force distribution can be effectively improved and the overall deformation of

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the plate is more uniform. Plates electromagnetic forming using discrete driving coils is presented in [21]. Results show that the electromagnetic force profile can be regulated by changing the cross sectional diameter and the location of the driving coils. A new coil system structure is presented in [22], which can generate uniform electromagnetic force on the entire plate and hence solving the main issue of the traditional sheet electromagnetic forming. This coil structure has been successfully used for processing mobile phone panels. Multiple sets of power supplies to energize multi-sets of driving coils along with a shaft-diameter bidirectional loading plate electromagnetic forming method is presented in [23]. This method can improve the performance of plate electromagnetic-forming with a better drawing coefficient (3.25) than that of the traditional drawing process (2.0-2.2). Reference [24] presented an attraction-type plate electromagnetic forming based on dual-frequency current method in which long and short pulse currents are provided through using two capacitor power supplies. Reference [25] proposed an axially movable electromagnetic forming system. The proposed forming method reduces the distance between the coil and the deformed plate during each discharging process and can increase the maximum deformation depth of the plate by 40mm than the traditional forming coil.

The above discussion shows that improving the electromagnetic force distribution and changing the electromagnetic force application method can solve some of the shortcomings of the conventional electromagnetic forming technology. However, some sheet forming performance problems have not been solved effectively yet.

This article is taking a step forward to solve some of these issues through proposing a new electromagnetic forming topology. The proposed structure comprises inner and outer ring double-coil loading to improve plate's deformation uniformity in the radial direction. The paper establishes an electromagnetic structural coupling model to numerically investigate the impact of physical dimensions of the coils on the electromagnetic force and the deformation formability. Furthermore, a numerical analysis comparing of the proposed method and the traditional electromagnetic forming is conducted and the plate forming uniformity under the double-coil loading method is discussed.

II. EMF PRINCIPLE AND THE PROPOSED TOPOLOGY

The general EMF topology is shown in Fig. 1. A fully charged capacitor is used to inject a pulse current through the coil which results in an induced eddy current within the plate [26]. A pulsed electromagnetic force is generated as a result of the interaction between the two currents. The generated electromagnetic (EM) force speeds-up the plate to accomplish the required formation [27].

Traditional flat coils will simultaneously produce axial and radial magnetic flux in the vicinity of the plate [7]. The bulging of the plate is mainly due to the axial electromagnetic force generated by the interaction of the radial magnetic flux density and the induced eddy current on the plate.

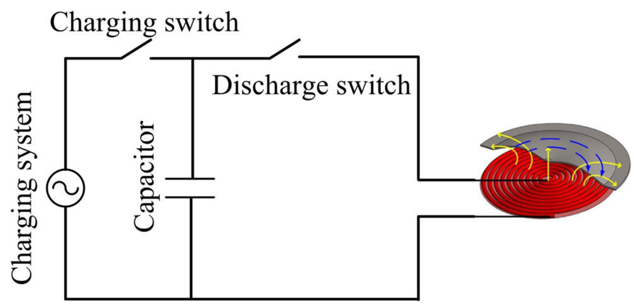

FIGURE 1. General electromagnetic forming topology [27].

Lorentz force in radial (F_r) and axial (F_z) directions are [13]:

$$F_r = J_\varphi \times B_z \quad (1)$$

$$F_z = J_\varphi \times B_r \quad (2)$$

where J_φ is the induced eddy current density of the plate in the circumferential direction, and B_z and B_r are respectively the axial and the radial components of the magnetic flux density [4].

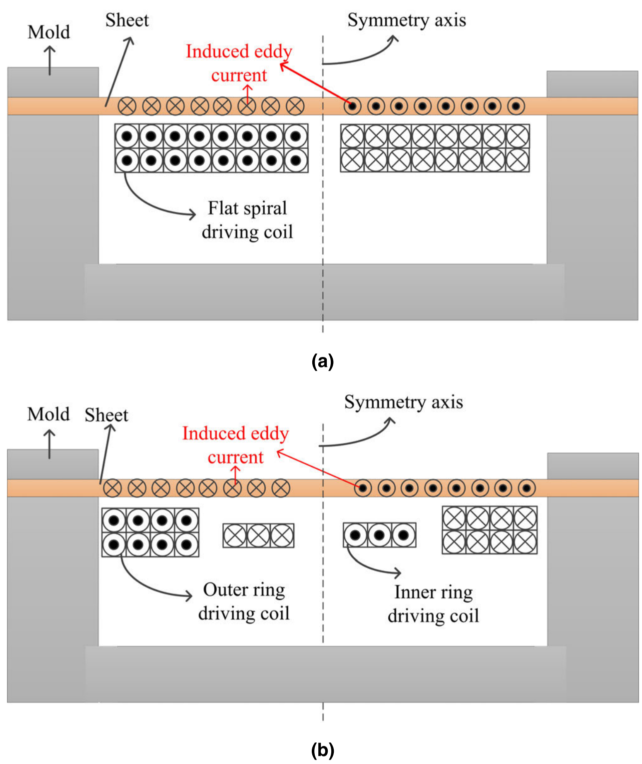

FIGURE 2. Geometrical structure of plate electromagnetic expansion (a) traditional flat spiral driving coil, (b) proposed double coil.

In conventional plate EMF, the plate spiral driving coil covers almost the entire processing area with a geometrical structure as given in Fig 2(a) [26]. However, this conventional structure comprises two problems. Firstly, the magnetic-flux density is almost focused in a radial direction which leads to a significant axial electromagnetic force component. The area with the largest electromagnetic-force is near the middle section of the plate's radius. As this area is subject to the largest electromagnetic force, the deformation speed of this area is the fastest which results in the smallest constraint at the plate center. Secondly, the axial force exhibits uneven distribution profile along the radial direction of the plate, which results in a slight forming amplitude at the edges of the plate and a huge convex contour near the center, which intensifies the non-uniformity of the plate radial forming.

To solve the problem of the poor performance of the conventional plate deformation method, a new EMF topology is proposed by employing inner and outer ring double coil plate whose geometrical structure is shown in Fig 2(b). The basic idea is to increase the inner radius of the outer driving coil ring to make it close to the edge of the die. Because the area with the largest electromagnetic-force appears near the half of the radius of the plate, a set of driving coils with a small number of turns are introduced inside the outer driving coil ring. A reverse pulse current is applied to the inner driving coil ring to establish a reverse strong pulsed magnetic field around the coil and hence weaken the magnetic flux density at the half radius of the plate. As the electromagnetic force is maximum at the areas close to the edge of the die, far away from the center of the plate, this can effectively suppress the excessive bulging of the center of the plate.

III. EMF STRUCTURE COUPLING MODEL

A. 2D AXISYMMETRIC MODEL

The physical process of the electromagnetic forming includes electric circuit, magnetic and mechanical fields. Finite element analysis has been widely used in the literature for the electromagnetic forming studies and obtained simulation results were in good agreement with the experimental results [28], [29]. Therefore, COMSOL software is employed to develop an electromagnetic-structure two-dimensional (2D) axisymmetric fully coupled model of the electromagnetic forming process of the plate [30].

The detailed geometric shapes of the flat coil, plate and epoxy resin in the numerical simulation model are shown in Figure 3 and are explained below:

-*Geometric structure parameters of flat spiral coil*: The traditional coil model has 15 layers of which each layer comprises 2 turns. The inner ring driving coil has 5 layers with 1 turn each while the outer loop coil has 8 layers of 2 turns each. The wire is made of copper of a cross-sectional area 2mm × 4 mm.

-*Geometric structure of the plate*: the circular plate material is AA5083-O with 200mm diameter and 2mm thickness.

B. DISCHARGE CIRCUIT

From the above discussion, it can be seen that the use of a single-power system produces a substantial axial electromagnetic force between the plate and the coil. In order to verify the advantages of electromagnetic forming of the inner and outer ring double-coil, this article uses a freewheeling discharge circuit, whose circuit parameters are listed in Table 1.

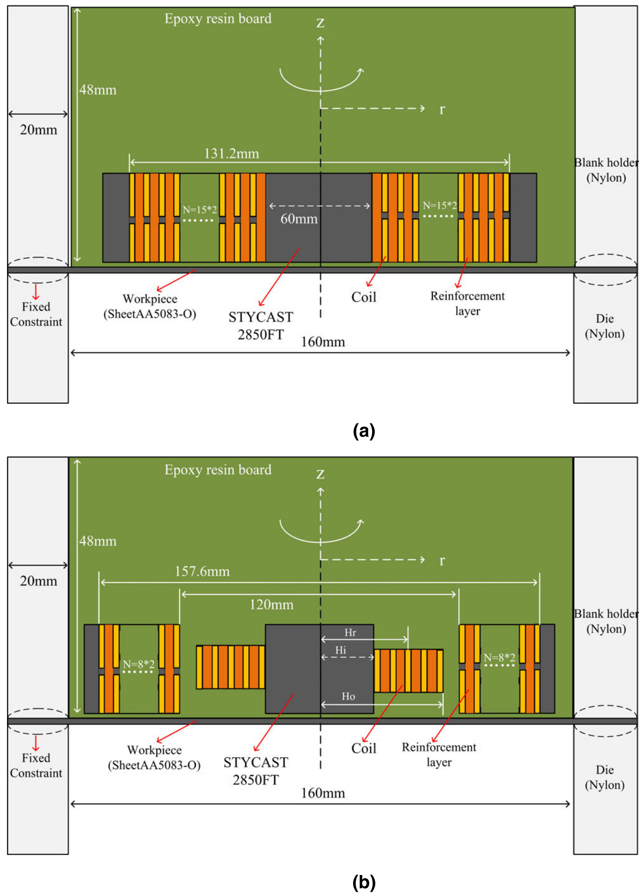

FIGURE 3. EMF system dimension (a) conventional flat spiral coil, (b) proposed double coil.

TABLE 1. Circuit parameters for the single-power system.

Symbol	Description	Value
C_0	Capacitance	320μF
U_0	Discharging voltage	3.4kV
R_0	Line resistance	20mΩ
L_0	Line inductance (measured using LC bridge)	5μH
R_d	Crowbar resistance	0.2Ω
S	Wire cross section area	2mm x 4mm

When there is no inner ring driving coil, the corresponding circuit diagram of the traditional coil EMF is as shown in Figure 4.

Kirchhoff's voltage and current equations of the equivalent circuit shown in Fig. 4 are:

$$\begin{cases} (R_0 + R)\boldsymbol{I_c} + (L_0 + L)\dfrac{d\boldsymbol{I_c}}{dt} + M_{m-w}\dfrac{d\boldsymbol{I_w}}{dt} - \boldsymbol{U_c} = 0 \\ R_w\boldsymbol{I_w} + L_w\dfrac{d\boldsymbol{I_w}}{dt} + M_{m-w}\dfrac{d\boldsymbol{I_c}}{dt} = 0 \\ \boldsymbol{U_c} = \boldsymbol{U_0} - \dfrac{1}{C}\displaystyle\int_0^t \boldsymbol{I_c}dt \end{cases} \tag{3}$$

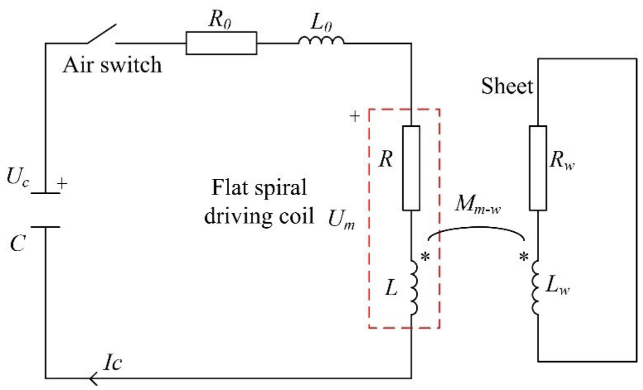

FIGURE 4. Equivalent circuit of the conventional plate EMF without inner ring driving coil.

$$\begin{cases} I_{\text{coil}} + I_{\text{c}} - I_d = 0 \\ I_d = 0 \quad U_{\text{c}} \geq 0 \\ I_d = \dfrac{U_c}{R_d} \quad U_{\text{c}} < 0 \end{cases} \tag{4}$$

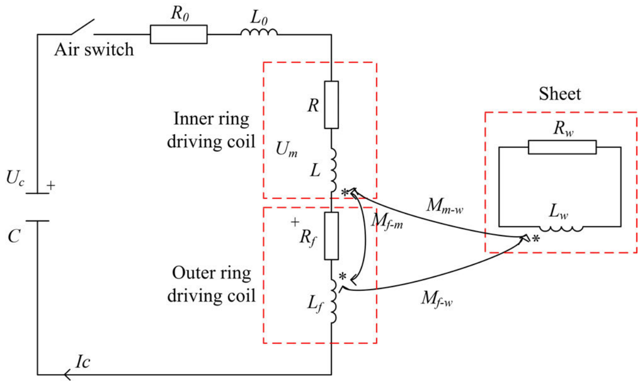

FIGURE 5. Plate EMF equivalent circuit using the proposed double coil.

By using the double coil proposed in this article, the equivalent circuit will be as shown in Fig. 5. Hence, the above equations will be:

$$\begin{cases} (R_0 + R + R_f)I_c + (L_0 - L + L_f)\dfrac{dI_c}{dt} \\ (M_{f-w} - M_{m-w})\dfrac{dI_w}{dt} = U_c \\ R_{\text{w}}I_w + L_{\text{w}}\dfrac{dI_w}{dt} + (M_{w-f} - M_{w-m})\dfrac{dI_c}{dt} = 0 \\ U_c = U_0 - \dfrac{1}{C}\displaystyle\int_0^t I_c dt \end{cases} \tag{5}$$

where I_w is the induced eddy current in the plate, I_{coil} is the coil current, I_d is the crowbar circuit current and U_c is the capacitor voltage [28].

C. MAGNETIC FIELD

Magnetic field module is used to calculate the magnetic flux density in the space domain and the induced current of the plate. Due to the pulse current in the flat spiral coil, a time varying magnetic field is produced in the vicinity of the coil. This time-varying magnetic-field can be represented by Maxwell's equations [31].

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} \tag{6}$$

$$\nabla \times \boldsymbol{E_\varphi} = -\frac{\partial \boldsymbol{B_z}}{\partial t} + \nabla \times (\boldsymbol{v_z} \times \boldsymbol{B_r}) \tag{7}$$

$$\nabla \cdot \boldsymbol{B} = 0 \tag{8}$$

$$\boldsymbol{J_\varphi} = \gamma \boldsymbol{E_\varphi} \tag{9}$$

where $\boldsymbol{E}$ is the electric-field intensity; $\boldsymbol{B}$ is the magnetic-flux density; $\boldsymbol{v}$ is the plate-speed; $\boldsymbol{J}$ is the induced eddy-current density; $\boldsymbol{\gamma}$ is the plate's conductivity. Subscripts $\boldsymbol{r}$, $\boldsymbol{\varphi}$, and $\boldsymbol{z}$ are respectively the radial, hoop, and axial components of a vector.

D. MECHANICAL FIELD

Due to the electromagnetic force exerted on the plate, it drives it to accelerate and deform. Hence, it is mechanical field analysis is essential. The used material of the plate is annealed-5083 aluminum that has the parameters listed in Table 2.

TABLE 2. Material properties of the plate.

Symbol	Description	Value
D	diameter	200mm
H	thickness	2mm
μ_r	Relative permeability	1
ε	Relative permittivity	1
ρ	Density	$2700 kg/m^3$
σ	Electrical Conductivity	3.72e7S/m
γ	Poisson ratio	0.33
E	Youngs modulus	68GPa
σ_{ys0}	Initial yield stress	95MPa

Under the action of the axial force, the plate is accelerating and deforming away from the plate spiral coil, satisfying Newton second law:

$$\boldsymbol{F} = \text{m}\boldsymbol{a} \tag{10}$$

Therefore, the plate deforms due to the electromagnetic-force. The plate's rotation fulfils the equilibrium equation below:

$$\nabla \cdot \boldsymbol{\sigma} + \boldsymbol{F} = \rho \frac{\partial^2 \boldsymbol{u}}{\partial t^2} \tag{11}$$

where $\boldsymbol{F}$ is the bulk density vector of the electromagnetic force, σ is the stress tensor of the plate, ρ is the plate density, and $\boldsymbol{u}$ is the tube displacement vector, which is assumed to be initially zero [31].

Electromagnetic-forming is a high-strain rate deformation process, with stress-strain characteristics reported in [27]. In this article, Cowper-Symonds material is used to simulate the AA5083-O plate and analyze its deformation process. The constitutive equation is:

$$\sigma = [1 + (\frac{\varepsilon_{pe}}{P})^m]\sigma_{ys} \quad (12)$$

where σ is the flow-stress of the plate throughout the high-speed deformation, m represents the strain-rate hardening, P is the viscosity, and σ_{ys} is the quasi static condition. For aluminum, $P = 6500$ and $m = 0.25$ [31].

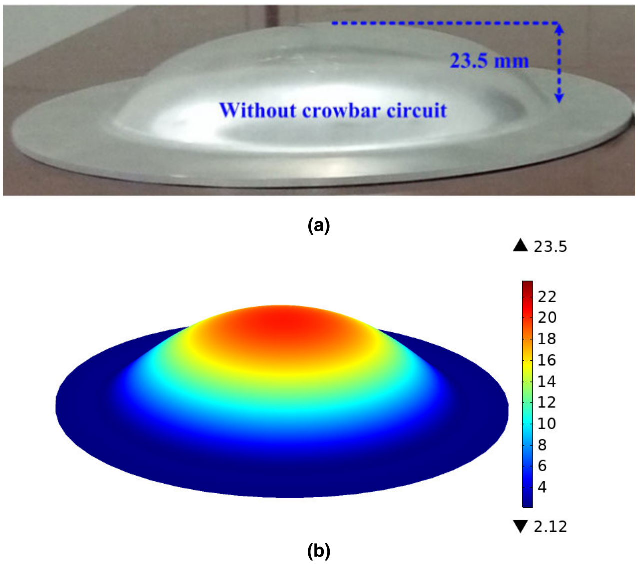

FIGURE 6. **Profile of sheet-forming (a) experimental results in [32], (b) simulation results using the proposed finite element model [mm].**

In [32], this model is used to study the forming efficiency in double sheet electromagnetic forming process. Fig 6 (a) shows experimental results published in [32] while Fig 6 (b) depicts the corresponding simulation results using the model proposed in this article.

Comparing the two plots in Fig. 6 shows that the simulation results are in good agreement with the experimental ones. Hence, the model developed in this article is accurate enough investigate the performance of the proposed double-coil plates as elaborated below.

IV. SIMULATION RESULTS

According to the above analysis, applying a reverse current to the inner ring driving coil can effectively weaken the induced eddy current at the center of the plate radius. Therefore, this section investigates the EMF of the proposed topology from the following two aspects.

A. AXIAL EM FORCE AND DEFORMATION BEHAVIOR

In the proposed topology, the inner ring driving coil is placed inside the outer ring driving coil, and its specific geometrical dimensions are as shown in Fig 3(b). In order to analyze the axial electromagnetic force acting on the plate and the plate deformation behavior, the parameters of the inner ring driving coil are changed in a wide range as follows:

-The inner-radius of the inner-ring driving coil (H_i) is changed from 12.8mm to 27.2mm in steps of 2.4mm,

-The outer-radius of the inner-ring driving coil (H_o) is changed from 24.4mm to 38.8mm in steps of 2.4mm.

-The equivalent radius of the inner ring driving coil (H_r), that maintains the cross-sectional area of the inner ring coil constant, is changed from 13.8mm to 37.8mm in steps of 4mm.

As can be seen above, at the initial state, H_i 12.8 mm, H_o is 24.4 mm, and H_r is 13.8 mm. At this state, the distance between the inner ring driving coil and the plate is 7.5 mm, while the distance between the outer loop coil and the plate is 4 mm. Under the assumption of maintaining two of the above three parameters unchanged, the influence of the variation of the third parameter on the axial electromagnetic force and uniform deformation of the plate is investigated below.

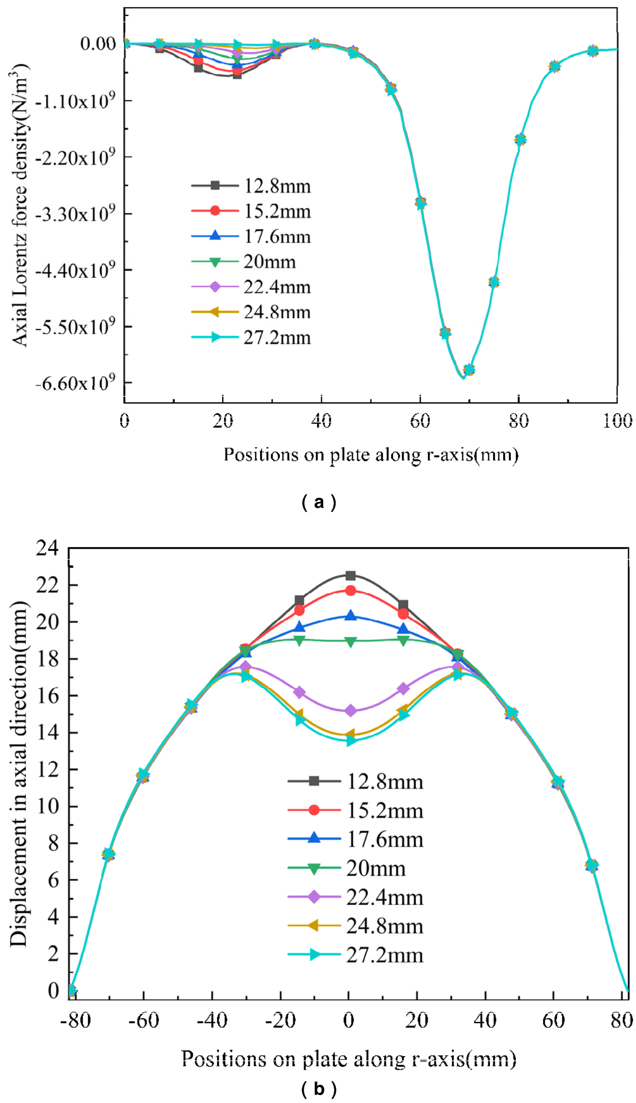

FIGURE 7. **Effect of the inner radius of the inner ring driving coil on the (a) axial EM force; (b) deformed contour.**

A.1 Effect of H_i: Fig 7 (a) depicts the influence of the inner radius of the inner ring-driving coil on the axial electromagnetic-force. It can be seen that the maximum axial electromagnetic force appears at the plate radius $r = 68$mm, which is close to the edge of the die. Also, it can be seen that the maximum axial electromagnetic force does not increase with the increase of H_i and it is almost the same all values of H_i. Near the center of the plate, the axial electromagnetic force gradually decreases as H_i increases.

Fig 7(b) shows the effect of the inner radius of the inner-ring driving coil on the deformation performance. It can be observed that as the inner radius of the inner-ring driving coil rises, the axial profile of the plate changes from "convex" to "concave". In the transition process, there is a critical value that makes the bulging of the plate shown as a relatively flat top, at which the bulging will be uniform. From the figure, the optimal inner radius of the inner ring driving coil is 20mm.

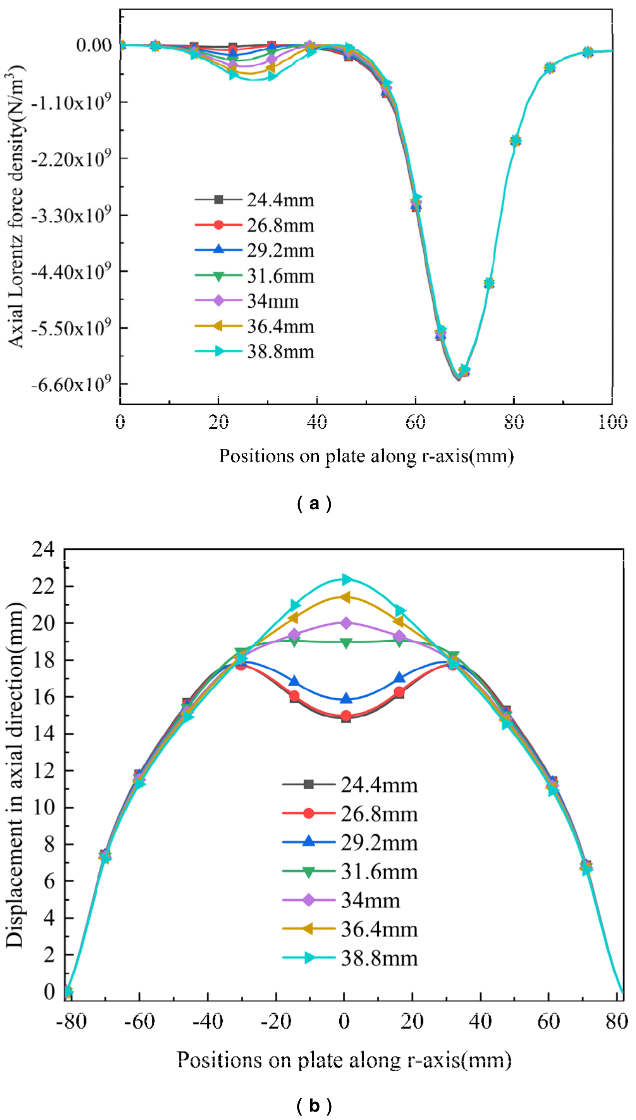

FIGURE 8. Effect of the outer radius of the inner ring driving coil on the (a) axial EM; (b) deformed contour.

A.2 Effect of H_o: Fig 8(a) shows the effect of the outer radius of the inner-ring driving coil on the axial electromagnetic force. It can be seen that the maximum axial electromagnetic force appears at the plate radius r = 68mm, which is consistent with the above result. However, near the center of the plate, as H_o increases, the axial electromagnetic force also increases, which is opposite to the trend when H_i is increasing.

Fig 8(b) shows the effect of the outer radius of the inner-ring driving coil on the deformation behavior. In contrary to the effect of H_i, as the outer-radius of the inner ring driving coil increases, the radial profile of the plate changes from "concave" to "convex". This transition occurs at an optimal value for $H_o = 31.6$mm at which the plate is formed uniformly. At the same time, by altering the geometric dimensions of the inner-ring driving coil, more possible plate contours can be obtained.

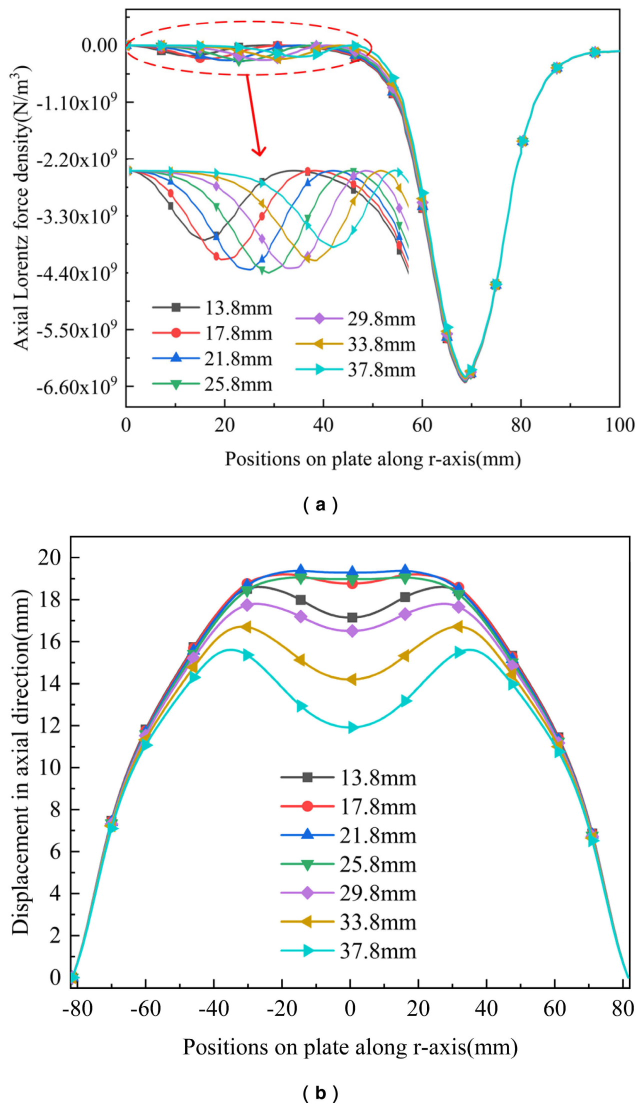

FIGURE 9. Effect of the equivalent radius of the inner ring driving coil on the (a) axial EM force, (b) deformed contour.

A.3 Effect of H_r: Fig 9(a) depicts the influence of the equivalent radius of the inner-ring driving coil on the axial electromagnetic-force. It can be seen that the maximum axial

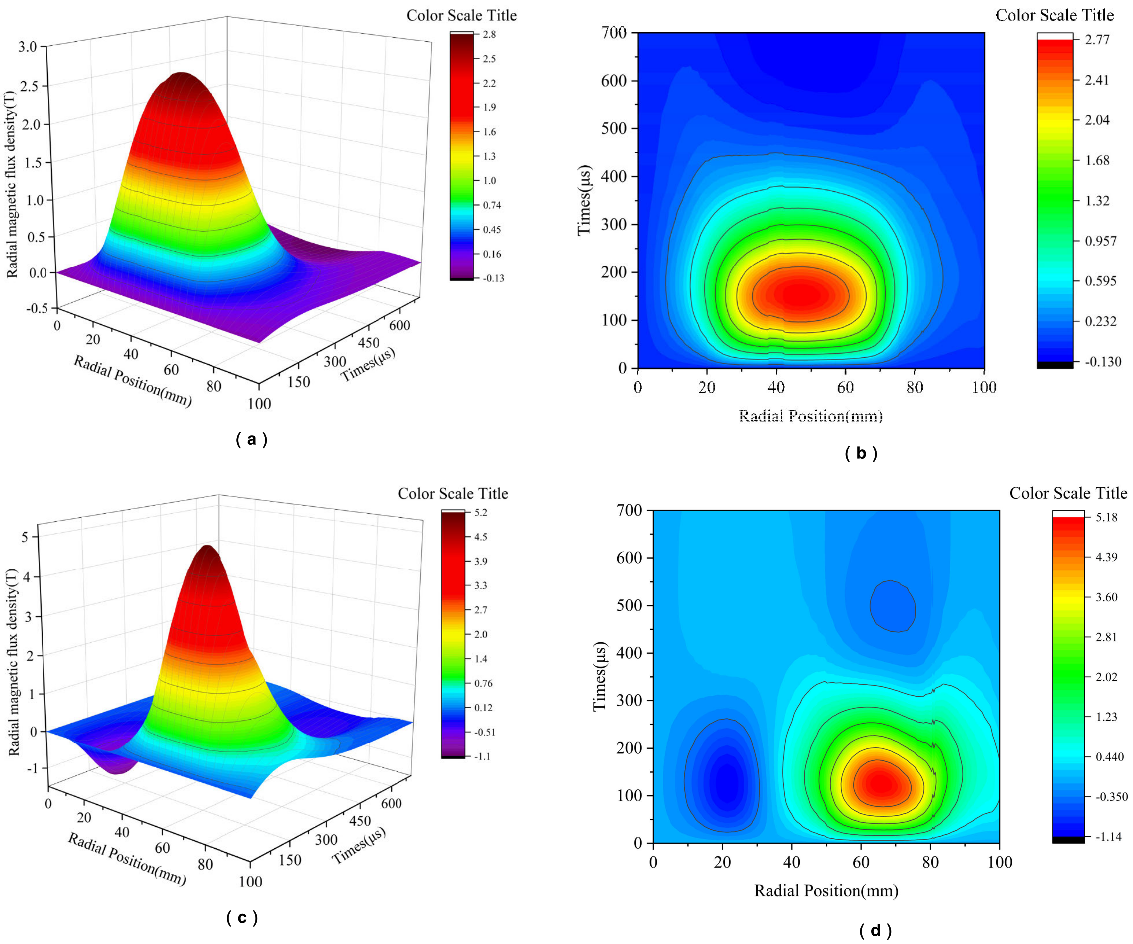

FIGURE 10. Three-dimensional cloud diagram of the radial magnetic flux density distribution with time and radial position. (a), (c) 3D cloud image of traditional and proposed double-coil and (b), (d) Top view of traditional and proposed double-coil.

electromagnetic-force appears at the plate radius r = 68mm, which is also consistent with the above results. However, near the center of the plate, as H_o increases, the axial electromagnetic force gradually moves away from the center of the plate. Fig 9(b) shows that by increasing of H_r, the contour of the plate changes from a concave shape to a relatively flat bottom, and then to a concave bottom. The critical part corresponding to the transition process gets the best uniform shape of the plate. In this example, there are two more suitable inner ring driving coils with equivalent radii of 21.8mm and 25.8mm; respectively.

The above results reveal that the proposed electromagnetic forming based on the proposed double-coil plate can regulate the distribution profile of the electromagnetic force. Reasonable geometrical parameters of the inner ring driving coils need to be designed to achieve optimum uniform deformation. In this article, the optimum design values of H_i, H_o, and H_r are found to be 20mm, 31.6mm, and 25.8mm; respectively.

B. COMPARATIVE ANALYSIS

This section compares and analyzes the effects of traditional flat coil and the proposed double-coil EMF on the radial magnetic flux, axial EM force, and the plate's deformation performance. The geometric dimensions of the traditional flat spiral coils and the double-coil plate forming used in the analysis are listed in Table 3; all other geometrical parameters are the same as in the above analysis. For accurate comparison, the discharging voltage is chosen to be 1.79kV when a conventional flat spiral coil is used and 3.4kV the double-coil is employed to ensure the same maximum plate deformation

TABLE 3. Geometrical dimensions of the flat spiral and double coils (mm).

		Height	Inner-radius	Outer-radius
Flat spiral coil		8.4	30	65.5
Double coil	Inner ring driving coil	4	20	31.6
	Outer loop coil	8.4	60	78.8

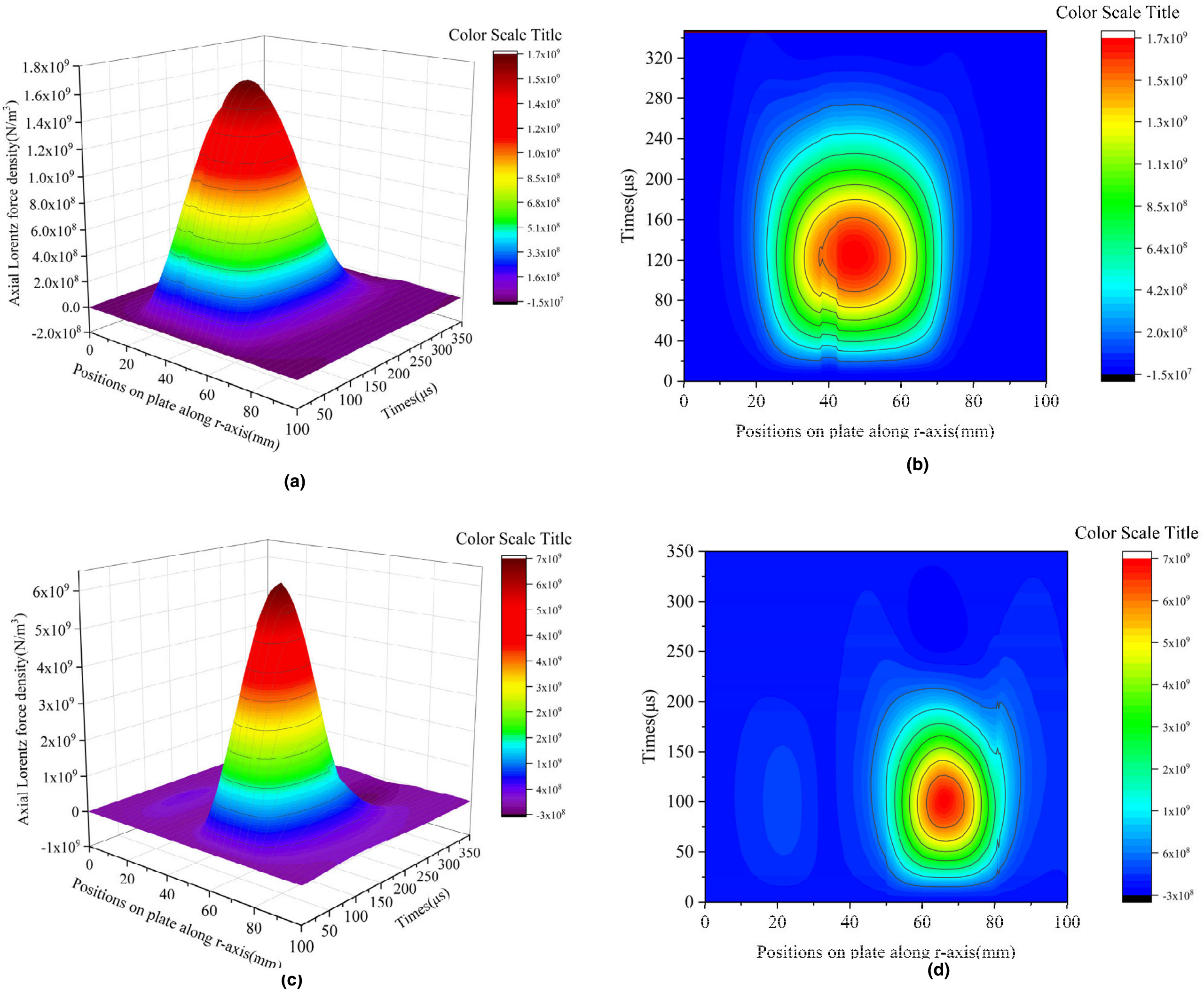

FIGURE 11. Radial electromagnetic force distribution with time and axial position. (a), (c) 3D cloud image of traditional and proposed double-coil and (b), (d) Top view of traditional and proposed double-coil.

when the two individual methods are used. It is worth noting that if the same discharging voltage is utilized, the maximum swelling amount of the plate under the two studied topologies will be inconsistent and uniformity comparison would not be accurate.

In the plate EMF process, the interaction of the radial magnetic-flux and the induced-eddy current determines the axial electromagnetic-force acting on the plate. Therefore, the radial magnetic-flux density distribution on the plate using the traditional flat spiral coil loading and the proposed inner and outer ring double-coil loading are obtained in three-dimensional (3D) plots as shown in Fig 10. It can be seen that when the traditional flat spiral coil loading is used, the radial magnetic flux is distributed in a large cone shape and almost covers the entire plate. The area with the largest radial magnetic flux appears close to the middle of the plate radius. The maximum magnetic flux density amplitude is 2.68T. On the other hand, by using the proposed dual-coil, the radial magnetic flux is distributed in a small cone shape, and is mainly concentrated in the area close to the edge of the die, while the magnetic flux at the middle of the plate radius is obviously weakened. The maximum radial magnetic flux density amplitude for this structure is 5.17T.

Fig 11 shows a cloud diagram of the profile of the axial electromagnetic-force when different coils are used for loading. When the traditional plate spiral coil is used for loading, the radial electromagnetic-force is distributed in a large cone. Because the driving coil covers almost the entire plate, the area with the largest electromagnetic-force appears close to the middle of the plate radius. This area receives the largest electromagnetic force, and hence the deformation speed is the fastest. The maximum radial electromagnetic force amplitude in this case is 1.72×10^9N/m^2. When the proposed double-coil topology is employed, the radial electromagnetic force is distributed in a small cone and the area near the edge of the die receives the largest electromagnetic force. Because

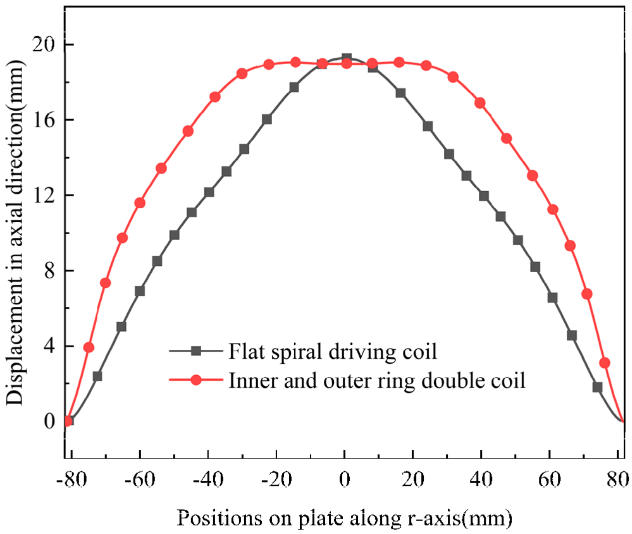

FIGURE 12. **Axial displacement along the radial direction of the plate.**

this area is far away from the center of the plate, its influence on the center of the plate is small, so that the plate has a better deformation effect. The maximum radial electromagnetic force amplitude in this case is $6.49 \times 10^9 \mathrm{N/m^2}$. It is to be noted that the electromagnetic force is concentrated on the side wall of the deformed plate, hence the distance between this side wall and the coil is almost constant under the constraint of the die. Consequently, for the same machined plate, the electromagnetic force is not seriously attenuated due to the increase of the distance during multiple discharge loads. This provides a possibility for repeated electromagnetic force to achieve electromagnetic deep drawing.

Fig 12 depicts the plate axial displacement in the radial direction when the conventional flat spiral coil and the proposed double-coil topologies are used for loading. When the plate spiral coil is used for loading, the axial displacement of the plate is convexly distributed, and the deformation at the center of the plate is the largest. When the proposed inner and outer ring double coils are used for loading, the axial displacement of the plate exhibits a relatively flat bottom, so that the overall deformation of the plate is more uniform, and the forming effect of the plate is improved.

In order to better reflect the deformation state of the plate during the forming process, the plate forming conditions at different times are investigated when different coils topologies are employed as shown in Fig. 13. It can be seen that at t $= 100\mu$s, when the traditional flat spiral coil is loaded, the plate first deforms close to the middle of the radius, while when the proposed coils are used, the area near the edge of the die first deforms. At t $= 900\mu$s, the plate reaches maximum deformation. When the traditional flat spiral coil is loaded, due to the minimum constraint of the plate center, the radial deformation is obviously uneven, showing a "taper" distribution. When the inner and outer ring double-coil are loaded, the electromagnetic force is concentrated close to the area near the edge of the die, so that the plate deforms uniformly in the radial direction.

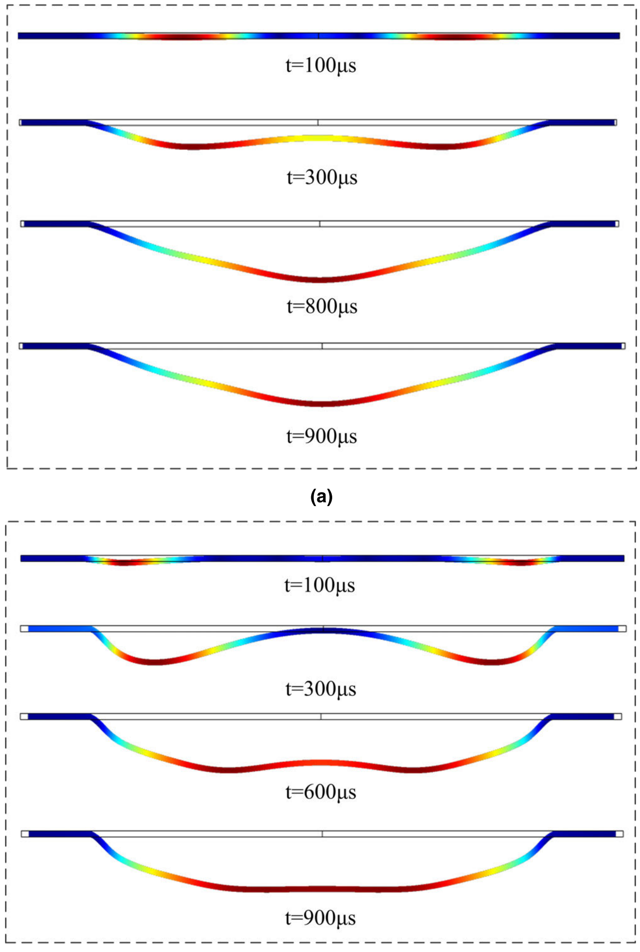

FIGURE 13. **Plate forming conditions at different times: (a) traditional flat spiral coil, (b) proposed double-coil.**

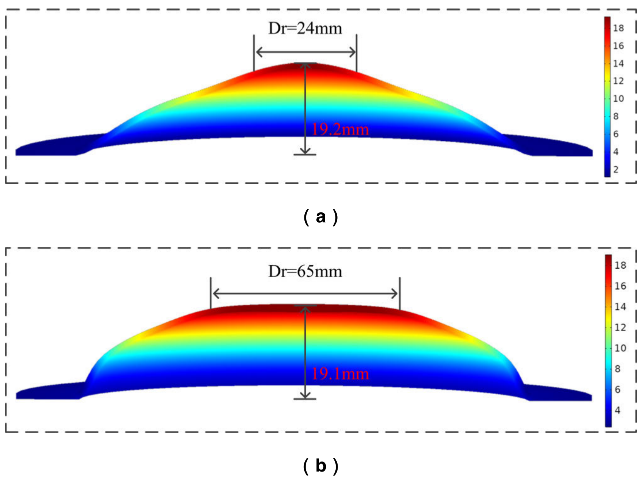

FIGURE 14. **Plate forming-contour: (a) conventional flat spiral-coil, (b) proposed double-coil.**

To attest the superiority of the proposed technique, maximum deformation value (D_r) is calculated for the plate under the two loading methods. D_r is the radial length less than or equal to 96% of the maximum deformation level. Fig. 14 reveals that, the conventional method results in

$D_r = 24$mm for a maximum bulging level of 19.2mm while D_r increases to 65mm when the proposed method is adopted.

V. CONCLUSION

This article proposes a new topology using inner and outer loop double- coil loading. The forming uniformity of the plate is analyzed separately using the proposed loading topology and is compared with the traditional loading method. Simulation results show that when the inner and outer ring double coils are used for loading, the magnetic flux close to the middle of the radius of the plate is significantly weakened due to the opposite impulse current applied by the inner ring coil and the radial electromagnetic-force is concentrated on the side wall of the deformed plate which leads to a better deformation effect and at the same time provides a certain possibility for repeated electromagnetic force to achieve electromagnetic deep drawing. Results also show that, when the discharging parameters of the system remain unchanged, there are optimum geometrical dimensions for the inner ring driving coil that results in the best electromagnetic forming effect. In addition, when the maximum deformation of the plate is the same, by applying a pulse current in the opposite direction to the inner ring driving coil, the axial electromagnetic-force distribution of the plate can be effectively changed, so that the electromagnetic force is more concentrated. The uniformity of the plate under the loading of the proposed inner and outer ring double-coil can be improved nearly three times compared with the traditional flat spiral coil loading. On the other side this method reduces the process efficiency due to the presence of a secondary coil which increases the total inductance of the equivalent circuit. This calls for further research to maintain the system efficiency while improving the uniformity of the plate.

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