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Analysis of Electromagnetic Force and Formability of Tube Electromagnetic Bulging Based on Convex Coil

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ABSTRACT Non-uniform axial deformation and tube wall thinning are the main issues restricting the further development of the tube electromagnetic bulging technology. Aiming at overcoming these issues, a tube electromagnetic bulging method based on convex driving coil is proposed in this paper. An electromagnetic-structure coupling model of the tube electromagnetic expansion process is established and the influence of detailed convex coil parameters on radial and axial Lorentz forces are analyzed. Results show that with the new proposed method, the homogeneous length of the tube axial deformation is 4.7 times that of the expansion loading with conventional driving coil. Meanwhile, the issue of tube wall thinning in the conventional electromagnetic bulging method is restrained due to the produced axial electromagnetic force using the proposed convex coil. The proposed tube electromagnetic bulging based on convex coil can effectively overcome the issues currently exist in the conventional tube electromagnetic bulging and promote wide industrial application of the electromagnetic forming technology.

INDEX TERMS Electromagnetic forming, tube wall thickness, non-uniform axial deformation.

I. INTRODUCTION

Electromagnetic forming (EMF) is a high speed pulsed technology that has been developed to replace conventional mechanical forming [1]–[3]. EMF improves the forming limit of metal materials to a great extent [4], [5]. Therefore, this technology has been widely applied to the processing of light alloys in aerospace, automotive and other industries [6]–[8].

Based on the nature of the processing object, EMF is classified into sheet and tube electromagnetic forming [9]. Tube electromagnetic forming is also categorized into pipe electromagnetic compression and pipe electromagnetic bulging [10]–[12]. For the electromagnetic bulging of pipe fittings, EMF comprises two technical drawbacks; axial nonuniformity caused by the tube end effect [13], [14], and of wall thinning caused by the increase of the tube radius [15].

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To improve the homogeneity of a tube forming, Cui *et al.* [16] adopted electromagnetic incremental forming approach to make the axial deformation of the pipe more uniform. At the same time, R-value criterion to evaluate the deformation uniformity was put forward. Yu *et al.* [17] studied the forming uniformity of pipe fittings by introducing a magnetic collector and reported that the homogeneity depends on the ratio of the tube length to the coil height. To solve the problem of axial non-homogeneity, Qiu *et al.* [18] and Huang *et al.* [19] presented a method that employs a concave driving coil to weaken the radial electromagnetic force in the middle of the tube and hence improving the tube-forming uniformity, and a novel R-L criterion of deformation homogeneity was proposed. To tackle the problem of a tube wall thickness, Qiu *et al.* [20] utilized the axial electromagnetic force to increase the axial flow of the pipe, and a magnetic pulse bulging method with three-coil axial compression was presented. This method is developed further into dual-coil and

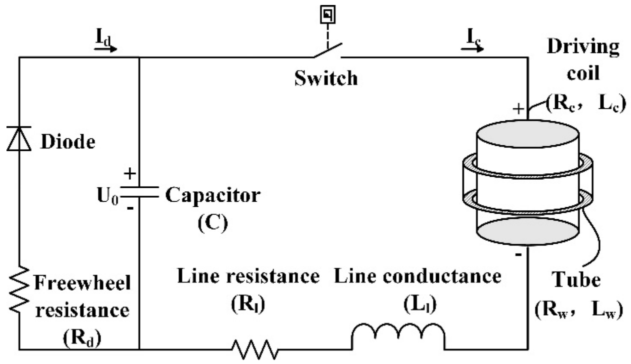

FIGURE 1. Schematic diagram of the electromagnetic tube bulging system.

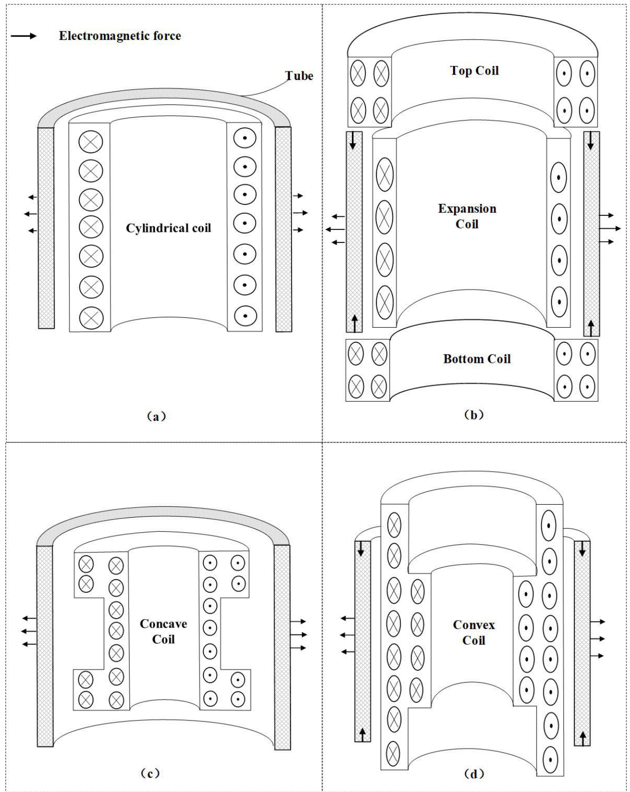

FIGURE 2. Electromagnetic expansion system. (a)Cylindrical coil, (b) three-coil, (c) concave coil, (d) proposed convex coil.

single coil tube magnetic pulse bulging with axial compression as the implementation of a three-coil system is relatively complicated [21], [22].

From the above discussion, the axial inhomogeneity and wall thinning issues in the tube EMF technology can be reduced by applying different electromagnetic forces throughout modifying the driving coil structure [23]. However, an electromagnetic force loading method that can solve these two technical issues simultaneously has not been presented in the literature yet [24]. Therefore, the main contribution of this paper is the presentation of a new convex driving coil structure based on the principle of electromagnetic forming and axial compression method.

The electromagnetic force distribution and the tubeforming performance under this new coil structure are analyzed through detailed finite element analysis.

II. ELECTROMAGNETIC BULGING PRINCIPLE

The tube electromagnetic bulging system mainly includes charging system, capacitor power supply, main discharging switch, driving coil and the object tube as shown in Fig 1. In the EMF process, the capacitor power supply is charged first through a charging circuit. The capacitor then discharges its energy to the driving coil by closing the discharging switch in the form of a pulsed current. The magnetic field of the coil and the generated eddy current induced on the tube produces electromagnetic force that accelerate and form the tube.

A. ELECTROMAGNETIC PRINCIPLE

In the tube electromagnetic forming process, a huge Lorentz force is generated due to the interaction between the magnetic flux and the tube induced eddy current. This force has two components; radial Lorentz $\boldsymbol{F_r}$ force and axial Lorentz force $\boldsymbol{F_z}$ that are calculated from:

$$\boldsymbol{F_r} = \boldsymbol{J_e} \times \boldsymbol{B_z} \tag{1}$$

$$\boldsymbol{F_z} = \boldsymbol{J_e} \times \boldsymbol{B_r} \tag{2}$$

where $\boldsymbol{J_e}$ is the eddy current density in the circumferential direction, $\boldsymbol{B_z}$ and $\boldsymbol{B_r}$ are the axial and radial components of the magnetic flux density; respectively.

Solenoid coils with height less than or equal to the height of the object tube are usually employed to generate the electromagnetic force on the tube during the traditional electromagnetic bulging process as shown in Figure 2(a). However, this method exhibits two issues: 1- the magnetic flux density on the tube is mainly concentrated in axial direction, which results in a serious thinning of the tube wall thickness because of the produced radial electromagnetic force; 2- the generated radial electromagnetic force distribution is uneven in the axial direction, which introduces a convex profile of a small magnitude at both ends of the tube and large magnitude in the middle. This contributes to further uneven axial deformation of the pipe fitting.

In order to overcome the problem of tube wall thickness reduction, the authors of this paper proposed an axial compression tube electromagnetic bulging method using a coil at the top and bottom of the tube as shown in Fig. 2 (b) to augment the radial magnetic flux density and hence strengthen the axial electromagnetic force [25]. To solve the issue of non-uniform axial deformation, the authors also proposed a tube electromagnetic bulging using a concave coil by reducing the number of ampere turns in the middle of the coil as shown in Fig. 2 (c) to reduce the induced eddy current and magnetic flux density in this area, and hence the radial electromagnetic force in the middle of the tube is reduced [20].

However, each of the above two mentioned methods solves only one of the problems associated with the electromagnetic

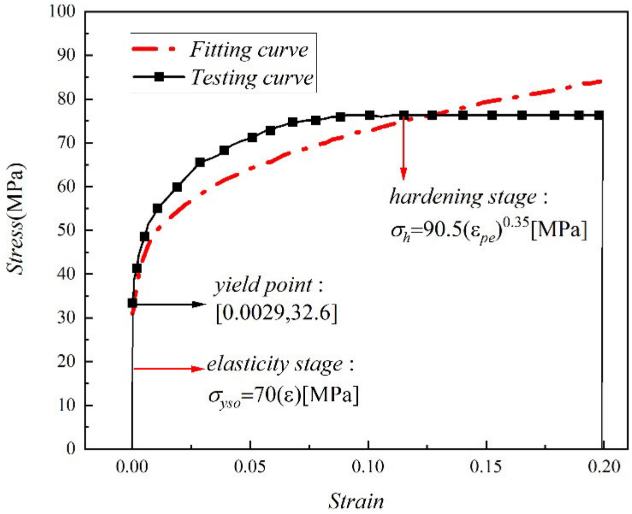

FIGURE 3. The stress-strain curve of the tested workpiece.

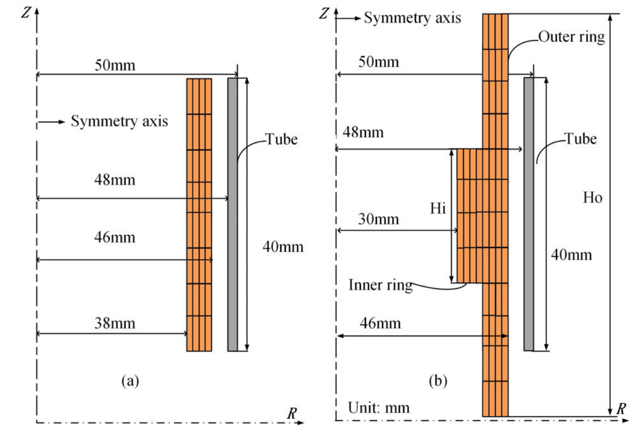

FIGURE 4. Geometrical dimensions of the developed finite element model, (a) traditional driving coil, (b) proposed convex driving coil.

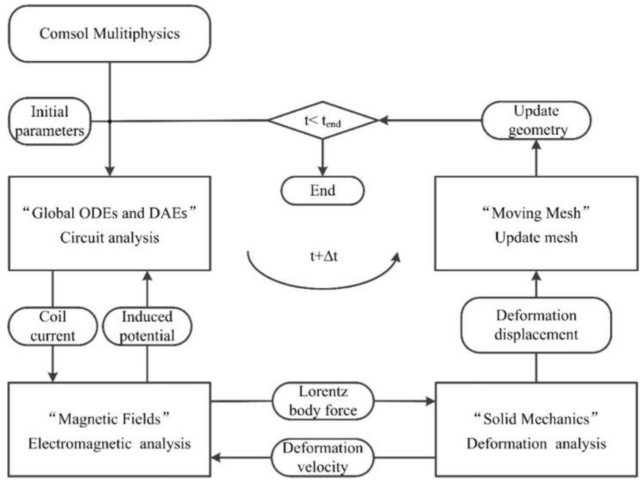

FIGURE 5. Flow chart of the electromagnetic tube expansion simulation.

bulging technology which makes them non cost-effective solutions. In order to solve these two issues simultaneously, this paper presents a new tube electromagnetic bulging based on convex coil. The new proposed coil structure is implemented by keeping the size of the top and bottom coils in consistency with that of the bulging coil and merging the three coils into one coil through reducing the inner and outer diameters of the three-coils so that the axial electromagnetic force can be loaded. For this structure, the electromagnetic force at both ends of the tube are of concave profile with large magnitude at both tube ends and small in the middle because the height of the merged coils is greater than that of the tube. The tube electromagnetic bulging based on convex coil is constructed by boosting the number of ampere turns in the middle of the coil to increase the induced eddy current and magnetic flux density in this area, and hence increasing the radial electromagnetic force in the middle of the tube. The new proposed structure is shown in Fig. 2 (d).

B. STRUCTURE PRINCIPLE

When the pipe is subjected to the electromagnetic force, according to Newton's law $F=ma$, the force and displacement of the tube satisfy the following equations:

$$\boldsymbol{F} + \nabla \bullet \sigma = \rho \frac{\partial^2 \boldsymbol{u}}{\partial^2 \boldsymbol{t}} \tag{3}$$

where σ is the stress tensor of the tube, $\boldsymbol{F}$ is the bulk density vector of the electromagnetic force, ρ is the tube density, and $\boldsymbol{u}$ is the displacement vector.

For the AA6061-O aluminum alloy studied in this paper, tensile test of a workpiece of 6.73 mm × 2.05 mm cross sectional area is carried out. The aluminum alloy stress-strain characteristic along with a fitting curve is shown in Fig. 3.

III. ELECTROMAGNETIC-STRUCTURE COUPLING MODEL

The electromagnetic-structure coupling finite element model of the tube electromagnetic expansion process is established using COMSOL software. The geometrical dimension of the developed model is shown in Fig. 4. The tube electromagnetic bulging simulation model as shown in Fig. 5 mainly includes:

-*Global ODEs and DAEs* module which simulates the external circuit and calculates the pulse current in the driving coil. The specific parameters of the external circuit are listed in Table 1. According to Kirchhoff's laws, the pulse current can be calculated using the below formulas:

$$R_1\boldsymbol{I_{coil}} + L_1\frac{d\boldsymbol{I_{coil}}}{dt} + \boldsymbol{V_{coil}} - \boldsymbol{U_c} = 0 \tag{4}$$

$$\boldsymbol{I_{coil}} + \boldsymbol{I_c} - \boldsymbol{I_d} = 0 \tag{5}$$

$$\boldsymbol{I_d} + \frac{\boldsymbol{U_c}}{R_d} = 0\ (if\ \ U_c < 0) \tag{6}$$

where $\boldsymbol{I_{coil}}$ is the coil current, $\boldsymbol{I_c}$ is the capacitance current and $\boldsymbol{I_d}$ is the continuous current.

-*Magnetics fields module* which simulates the time-varying electromagnetic field and computes the magnetic flux density, induced eddy current and the electromagnetic force distribution. Based on the Maxwell equations, the tube domain

TABLE 1. Parameters of the external circuit and workpiece.

Symbol	Description	Value
1- Circuit		
C	Capacitance	160 μF
L_1	Line inductance	12 μH
R_1	Line resistance	0.035 Ω
R_d	Crowbar circuit resistance	0.267 Ω
2-Workpiece		
	Inner diameter	96 mm
	Outer diameter	100 mm
	Density	2700 kg/m^3
	Electrical conductivity	3.03 x10^7 S/m
	Initial yield stress	32.6 MPa
	Poisson's ratio	0.33
	Young's modulus	70 GPa

equations can be expressed as follows:

$$\nabla \times \left(\frac{1}{\mu}\nabla \times \boldsymbol{A}\right) + \gamma\frac{\partial \boldsymbol{A}}{\partial \boldsymbol{t}} = 0 \tag{7}$$

$$\boldsymbol{J}_{\boldsymbol{\varphi}} = \gamma \boldsymbol{E}_{\boldsymbol{\varphi}} \tag{8}$$

where $\boldsymbol{A}$ is the magnetic vector potential, $\boldsymbol{E}$ is the induced electric field strength in the pipe fitting, $\boldsymbol{\gamma}$ is the conductivity of the pipe, and the subscripts $\boldsymbol{r}$, $\boldsymbol{\varphi}$ and $\boldsymbol{z}$ represent the radial, hoop and axial components of a certain vector; respectively.

-*Solid Mechanics module* which simulates the tube dynamic deformation process. Cowper-Symonds model is used to simulate the tube based on the following equations:

$$\sigma_{ys} = \begin{cases} E\varepsilon & \sigma_{ys} < \sigma_{yso} \\ \sigma_{ys0} + A\varepsilon_{pe}^{B} & \sigma_{ys} \geq \sigma_{yso} \end{cases} \tag{9}$$

$$\sigma = [1 + (\frac{\varepsilon_{pe}}{P})^m]\sigma_{ys} \tag{10}$$

where E is the young's modulus, σ is the flow stress when the tube material deforms at a high speed, m is the strain rate hardening parameter, P is the viscosity. A and B are constants; 90.5 and 0.35, respectively and σ_{yso} is the initial yield stress of the workpiece, ε_{pe} is the plastic strain. $P = 6500$, $m = 0.25$ are usually used for aluminum.

-*Moving Mesh model* which is used to update the finite element mesh that varies with the tube expansion. The outer boundary of the near field air domain and the coil domain boundaries are assumed to be fixed. The near field air and the tube domains are considered of free deformations.

The authors utilized this model to investigate the tube electromagnetic bulging using a concave coil in a previous publication [18] and validated the simulation model through experimental measurements as shown in Fig. 6. The error between simulation and experimental results in the tube deformation length in the axial direction was found to be less than 2%. This reveals the high accuracy of the developed model.

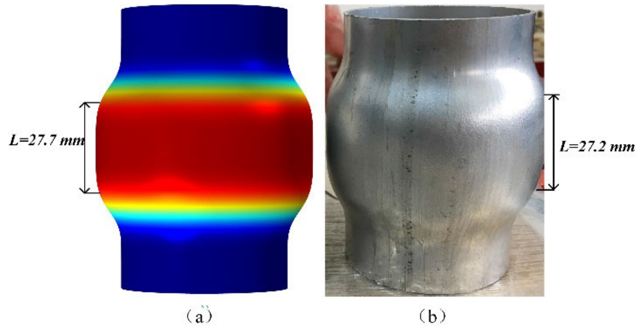

FIGURE 6. Results of tube electromagnetic bulging comparison based on concave coil, (a) simulation, (b) experimental [18].

IV. INFLUENCE OF CONVEX COIL STRUCTURE PARAMETERS ON THE TUBE ELECTROMAGNETIC BULGING

The distribution of the radial electromagnetic force mainly affects the uniformity of the tube axial deformation while reduction in the tube wall thickness is influenced by the distribution of the axial electromagnetic force. This section investigates the tube electromagnetic bulging from these two aspects.

A. EFFECT OF COIL STRUCTURE ON RADIAL ELECTROMAGNETIC FORCE AND AXIAL DEFORMATION UNIFORMITY

Analysis is performed on a tube of 40 mm height. The initial dimensions of the convex coil shown in Fig. 4 (b) are: height of the outer ring $\boldsymbol{H_o}$ is 64 mm, inner diameter of the outer ring is 76 mm, outer diameter of the outer ring is 92 mm, inner diameter of the inner ring is 60 mm, height of the inner ring $\boldsymbol{H_i}$ is 36 mm.

The effects of the heights $\boldsymbol{H_o}$ and $\boldsymbol{H_i}$ on the radial electromagnetic force and axial deformation homogeneity are explored by changing each in a wide range while maintaining all other parameters. The amplitude of the pulse current density of the convex coil is set at $3.1 \times 10^8\ A/m^2$.

Fig. 7 (a) shows the influence of the height $\boldsymbol{H_o}$ of the outer ring on the radial electromagnetic force as a function of the tube positions along z-axis. It can be observed that the peak value of the radial electromagnetic force is located at the middle of the pipe fitting, and it gradually moves toward both ends of the tube with the increase of $\boldsymbol{H_o}$. Therefore, the peak position of the radial electromagnetic force is determined by the height of the outer ring. Fig. 7 (b) shows the impact of $\boldsymbol{H_o}$ on the axial deformation homogeneity. As shown, the axial deformation of the tube is of convex profile when the maximum of the radial electromagnetic force is in the middle of the pipe fitting and it becomes concave when the amplitude of the radial electromagnetic force appears at both ends of the tube. Obviously, there is a critical value at which the tube can be uniformly deformed. The critical value of the axial uniform deformation of the tube under investigation appears at $\boldsymbol{H_o} = 60$ mm.

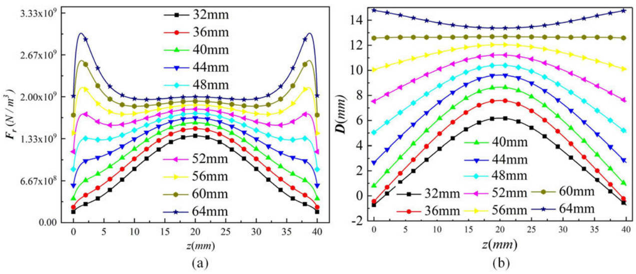

FIGURE 7. Effect of H_o on (a)radial electromagnetic force, (b) axial deformation homogeneity.

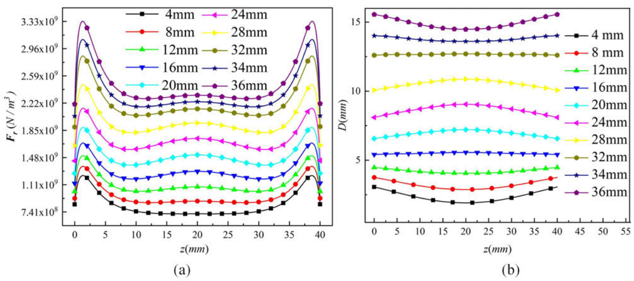

FIGURE 8. Effect of Hi on (a) radial electromagnetic force, (b) axial deformation homogeneity.

The effect of H_i on the radial electromagnetic force and the axial deformation homogeneity is shown in Fig. 8. There are two critical values of the inner ring height H_i, which facilitates more uniformity for the axial deformation of the pipe. From Fig. 8, the critical values of H_i are 16 mm and 32 mm.

The above analysis shows that the radial electromagnetic force distribution characteristics can be changed by using the proposed convex coil, hence the axial deformation uniformity of the tube can be improved. It is worth noting that for specific pipe fittings, reasonable convex coil structure parameters need to be designed in order to obtain more homogeneous axial deformation.

B. EFFECT OF COIL STRUCTURE ON THE AXIAL ELECTROMAGNETIC FORCE AND TUBE WALL THICKNESS

Fig. 9 shows the effect of H_o on the axial electromagnetic force and the wall thickness reduction R while Fig. 10 depicts the effect of H_i on the same two parameters. In both figures, the left y-axis (F_z, shown in blue colour) refers to the peak value of the axial electromagnetic force on the upper half of the tube during the bulging process while the right y-axis (R, shown in red colour) refers to the reduction of the tube wall thickness at the central node at the end of the bulging process. It is worth mentioning that the axial electromagnetic force is of positive values which means the tube is subjected to a compressive axial force from the end to the center, as can be observed from Fig. 2(d). The axial flow of the material increases with the augmentation of the compressive axial force, which restrains the reduction of wall thickness at the center of the tube.

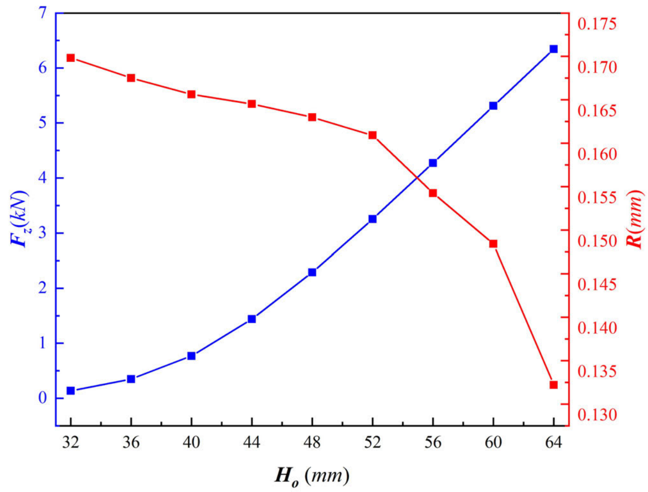

FIGURE 9. Effect of H_o on the axial electromagnetic force and wall thickness reduction.

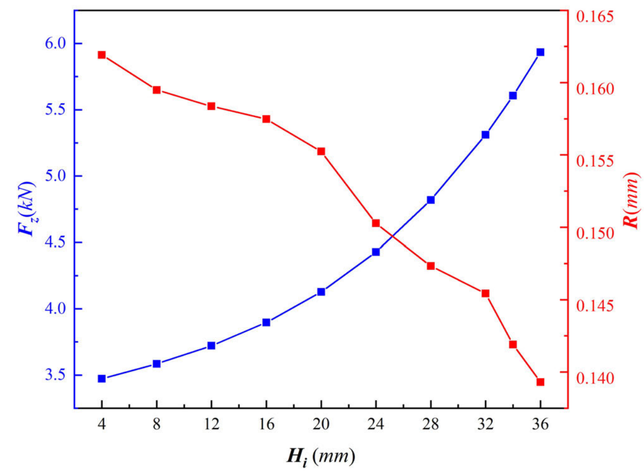

FIGURE 10. Effect of H_i on the axial electromagnetic force and wall thickness reduction.

Results show that the axial electromagnetic force increases with the increase of H_o or H_i. Results also show that the thinning amount of the tube wall thickness decreases gradually with the increase of H_o or H_i. This indicates that the axial electromagnetic force can be increased and the wall thickness reduction of the tube can be suppressed by adjusting the coil structure.

V. ANALYSIS OF TUBE ELECTROMAGNETIC BULGING BASED ON CONVEX COIL

To highlight the advantages of the tube electromagnetic bulging based on convex coil, conventional driving coil and convex coil are employed to generate electromagnetic force to the same pipe. The axial deformation uniformity and the wall thickness reduction are analyzed and compared. Based on the analysis of the above analysis, the coil structure parameters utilized in this comparison are as shown in Table 2. The maximum radial displacement of both coils is assumed to

TABLE 2. Structural parameters of conventional cylindrical coil and the proposed convex coil.

		Height (mm)	Inner diameter (mm)	Outer diameter (mm)
Cylindrical coil		40	76	92
Convex coil	Outer ring	60	76	92
	Inner ring	32	60	76

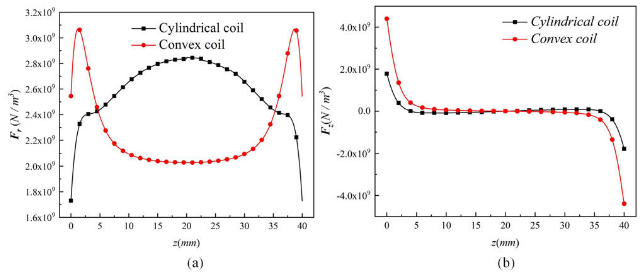

FIGURE 11. Electromagnetic force density, (a) radial electromagnetic force, (b) axial electromagnetic force.

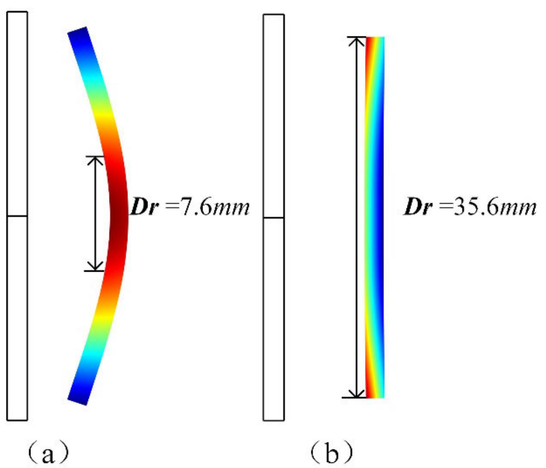

FIGURE 12. Tube forming profile with different driving coils, (a) conventional coil, (b) convex coil.

be 10 mm. For such displacement, the discharge voltage of the traditional driving coil should be set to 3.55 kV, while the discharge voltage of the convex coil should be set to 3.7 kV.

Fig. 11 shows the distribution of the electromagnetic force density on the tube when the conventional and proposed driving coils are utilized. Apparently, the maximum amplitude of the radial electromagnetic force (Fig. 11(a)) is located at the axial middle region of the pipe fitting when the conventional driving coil is employed. On the other hand, the peak value of the radial electromagnetic force is located at both ends of the axial direction of the tube when the proposed convex coil is used. Meanwhile, the amplitude of the axial electromagnetic force density by employing the proposed coil structure is twice that of the traditional driving coil as shown in Fig. 11(b). Fig. 12 shows the forming profile of the tube when the two investigated driving coils are used. Results show that the tube is of convex shape after bulging process when the traditional driving coil with convex radial

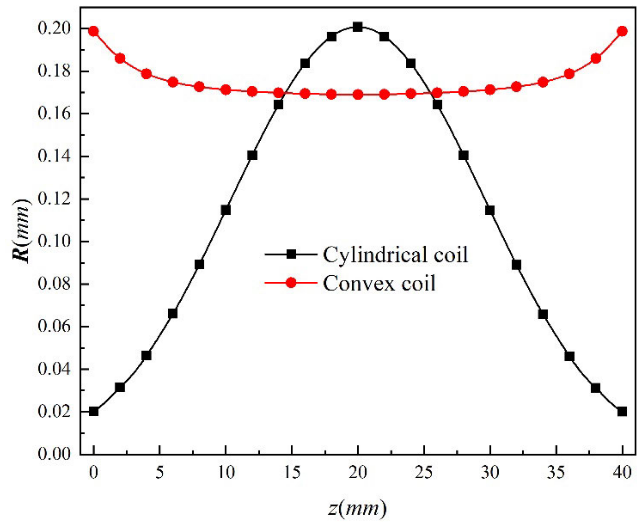

FIGURE 13. Wall thickness reduction of pipe fitting with different driving coils.

electromagnetic force distribution is used. On the other hand, the tube exhibits high uniformity after expansion by employing the proposed convex coil with concave radial electromagnetic force distribution. In order to quantify this uniformity, the parameter D_r is introduced to describe the homogeneous deformation range. D_r is defined as the axial length when the pipe fitting displacement is greater than 98% of the maximum radial displacement. The axial uniformity D_r is 7.6 mm when the traditional driving coil is used and it is 35.6 mm when the proposed convex coil is utilized which is 4.7 times the value obtained from the traditional coil. This proves the electromagnetic bulging based on the proposed convex coil can effectively enhance the axial deformation uniformity of the pipe.

Fig. 13 depicts the wall thickness reduction of the pipe fitting with the two investigated coils. It is to be noted that a comparison of the wall thickness reduction R is meaningful only when the bulging amount is the same. For a tube expansion of 10 mm, the thinning amount of the tube wall thickness at the center is 0.2 mm when a conventional coil is used and 0.169 mm when the proposed convex coil is used. These results reveal that the wall thickness reduction can be suppressed by 15% when the proposed coil is adopted. The reduction in the tube wall thickness after the bulging process makes it more prone to breakup due to the reduction of its mechanical strength at the central area [26]. The electromagnetic bulging based on convex coil can further restrain the reduction of wall thickness at the center of the tube and improve the mechanical strength of the formed tube while ensuring uniformity of the axial deformation.

VI. CONCLUSION

In order to simultaneously solve the problems of inhomogeneous axial deformation and wall thickness reduction in conventional tube electromagnetic bulging, a tube electromagnetic expansion method based on convex coil is proposed in this paper. The proposed method enables the workpiece to be loaded with more reasonable electromagnetic forces. Results show that the proposed convex coil provides concave distributed radial electromagnetic force on the pipe and improves the uniformity of the tube axial deformation. Compared with the conventional coil structure, the proposed coil structure provides more axial electromagnetic force, which increases the axial flow of the material, and restrains the thinning of the wall thickness during the deformation process. Thus, the utilization of the proposed convex coil can solve the problems of non-uniform axial distribution of electromagnetic bulging and thinning of the tube central wall thickness at the same time. Further experimental measurements should be carried out to validate the simulation results in this paper. It is also to be noted that while this paper focuses on investigating the influence of detailed convex coil parameters on radial and axial Lorentz forces, a detailed optimization analysis is essential to design the convex coil structure parameters for better performance of the electromagnetic bulging process at a reasonable cost.

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