Parametric Simulation Analysis of the Electromagnetic Force Distribution and Formability of Tube Electromagnetic Bulging Based on Auxiliary Coil

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ABSTRACT Tube electromagnetic bulging has been given much attention due to its superior advantages in the field of light alloy processing. However, the conventional tube electromagnetic bulging process exhibits some critical issues that restrict its wide industrial applications. This includes non-uniform axial deformation and poor forming performance such as wall thickness thinning. This article proposes a cost-effective solution for such issues through simultaneous radial and axial electromagnetic force loading using an auxiliary driving coil. In this regard, the influence of the auxiliary coil geometrical parameters on the electromagnetic force distribution and tube forming performance is investigated using electromagnetic-structure coupling model of the bulging process. The robustness of the new proposed method is validated by comparing its electromagnetic force distribution and tube forming performance with the traditional cylindrical coil method, currently used by industry practice. Numerical results show that the introduction of the auxiliary coil may effectively weaken the radial electromagnetic force at the end of the tube and solve the uneven axial deformation issue. Based on the obtained results, the maximum uniform deformation area is increased from 6.9mm to 35.1mm. The tube relative wall thinning issue is reduced and the relative wall thickness reduction of the pipe is found to be 0.01661. The axial electromagnetic force can be further improved by adjusting the geometrical parameters of the coil and the proposed electromagnetic bulging can effectively increase the uniform deformation range of the tube.

INDEX TERMS Forming technology, driving coil, electromagnetic force, electromagnetic tube expansion, deformation nonuniformity.

I. INTRODUCTION

Lightweight alloys are widely used in several applications including aerospace, automotive industry and other fields [1]. For example, the weight of the aircraft body is reduced by 5kg, while the effective commercial load can be increased by 50kg when the body is made of lightweight alloy [2]. Similarly, when lightweight alloy material is used in manufacturing cars, the weight is reduced by 10%, and the fuel consumption is reduced by 6% to 8% [3]. However, alloy materials exhibit low room temperature forming plasticity, poor local drawability and they are prone to cracks and possessing large spring back which makes the traditional alloy processing technology not ideal [4], [5]. Electromagnetic-based high-speed forming technology employs pulsed electromagnetic force to process metal materials. Compared with traditional machining, electromagnetic forming has the following advantages: 1) high strain rate (10\(^3\) - 10\(^5\) s\(^{-1}\)), which...
can improve the plastic deformation ability of the material and increase its forming limit by 5-10 times [6], [7]; 2) Contact force can improve the stress distribution of the workpiece and improve the surface quality of metal materials [8]–[10].

According to the type of the workpiece, the electromagnetic forming can be divided into sheet and tube electromagnetic forming. On the other hand, based on the loading method of the electromagnetic force, the tube electromagnetic forming is divided into electromagnetic expansion and compression [11], [12]. In tube electromagnetic forming, the workpiece deformation uniformity and the wall thickness thinning have been considered the main issues that attracted many research attempts in the literature. For instance, Qiu Li et al. proposed concave driving coil structure for tube loading [13]. Reported results show that with such coil structure the radial electromagnetic force on the middle section of the tube is significantly weakened which improves the uniformity of the tube. A dual-coil axial compression electromagnetic bulging method is proposed in [14]. Results show that the dual-coil can provide radial and axial electromagnetic forces on the workpiece at the same time which enhances the bulging uniformity of the formed workpiece and reduce the thinning of the wall thickness. In [15], the uniform radial deformation trend of aluminum tube is investigated during electromagnetic compression based on sequential coupled numerical simulation and experimental design optimization methods. Results show that this trend depends on the tube-to-coil length ratio. An electromagnetic asymptotic forming which changes the discharge position of the coil to make the tube axial deformation more uniform is presented in [16]. A uniform pressure coil is presented in [17], to improve the spatial distribution of the electromagnetic force. A 3D model to analyze the electromagnetic field distribution in an electromagnetic forming system with field shaper is presented in [18]. Results show that the field shaper not only enhances the magnetic field, but also distributes the magnetic field uniformly along the workpiece.

From the above literature review it can be observed that different electromagnetic forces can be applied by changing the driving coil structure or by introducing auxiliary tools in order to solve one of the common electromagnetic forming issues: uneven axial deformation of the workpiece or thinning of the wall thickness. Some electromagnetic force loading methods were proposed in the literature to solve these two technical issues simultaneously. When the axial size of the shaped tube is small, it will be difficult to use intermediate bulging coil and to change the coil structure. At the same time, the overall coil strength, coaxiality, and insulation performance will also be greatly affected.

This article presents a new method that can be used for any tube size to improve the uniformity of the tube and weaken the wall thickness at the same time. The method is based on using upper and lower auxiliary coils on the periphery of the tube. The axial uniformity and relative wall thickness reduction of the tube are investigated through a detailed electromagnetic-structure coupling model. The effects of the bulging coil height, distance between the auxiliary coils and the tube, and the distance between the upper and lower auxiliary coils on the radial electromagnetic force, deformation behavior and tube relative wall thickness reduction are investigated. Furthermore, the electromagnetic force distribution under two different loading methods; traditional cylindrical coil forming and auxiliary coil forming are compared and analyzed, and the uniformity of tube forming based on auxiliary coil loading is discussed.

It is to be note that in [2], the driving coil is placed inside the pipe, which makes it difficult to achieve effective bulging. In [14], a double-coil axial compression pipe electromagnetic bulging is proposed, which simultaneously realizes the axial and the radial bidirectional loading. In this method the driving coils are placed on the top and bottom of the pipe fitting to provide reasonable electromagnetic force distribution. However, in the proposed topologies in [2] and [14], the height of the bulging coil is much larger than the height of the pipe which results in a higher radial electromagnetic force at the end of the pipe than at the middle section which reduces the effectiveness of the proposed methods. Therefore, the introduction of the auxiliary coil in this article, will deteriorate the radial electromagnetic force at the pipe ends and helps improve the uniformity of the pipe.

II. BASIC PRINCIPLES OF ELECTROMAGNETIC FORMING AND THE PROPOSED AUXILIARY COIL

The tube electromagnetic forming system mainly includes a charging system, a capacitor power supply, a main discharge switch, a driving coil and the tube as shown in Fig. 1. At first the capacitor is fully charged through a charging circuit, then it discharges its saved electrostatic energy into the driving coil by closing the discharge switch. Hence a pulse current is generated in the driving coil. At the same time, an induced eddy current is generated in the tube outside the driving coil. The interaction between pulsed current and the tube induced eddy current drives the tube to accelerate and achieve bulging [19]–[21].

Owing to the interaction of the magnetic flux and the induced eddy current of the tube, a huge Lorentz force is generated. This force has two components; radial Lorentz
force $F_r$ and axial Lorentz force $F_z$, which are calculated from:

$$F_r = J_\phi \times B_z$$

$$F_z = J_\phi \times B_r$$

where $J_\phi$ is the induced eddy current density of the tube in the circumferential direction, and $B_z$ and $B_r$ are respectively the axial component and the radial component of the magnetic flux density.

In the traditional tube electromagnetic bulging process, a single cylindrical bulging coil is usually placed inside the tube. The height of the bulging coil is less than or equal to the height of the tube, as shown in Fig. 2(a). However, in this method the magnetic flux density is mainly concentrated in the axial direction of the tube; hence the tube loading is mainly a radial electromagnetic force component. When the tube is bulged, the radius of the tube increases and results in thinner wall thickness and low mechanical strength, which does not comply with the industry requirements. Moreover, the radial electromagnetic force generated by the bulging coil is unevenly distributed along the axial direction of the tube, which leads to a tube convex profile with a small forming width at the end of the tube and a large forming width at the middle section, which further aggravates the unevenness of the tube axial forming.

In order to overcome the issue of the tube non-uniform axial forming, the authors have proposed a concave coil inside the tube as shown in Fig. 2(b) [13]. The coil is constructed by reducing the number of ampere-turns in the middle part to reduce the amount of deformation in the middle section of the tube. While the quality of tube forming has been improved, winding up the coil is difficult and calls for complex analysis. Also, an electromagnetic expansion method has been presented in [14]. In this method, bulging coils are placed at the top and bottom of the tube as shown in Fig. 2(c) to simultaneously provide radial and axial electromagnetic forces and hence reducing the thinning of the wall. However, because of the lack of intermediate expansion coil, the generated radial electromagnetic force is substantially reduced and a large initial capacitor energy storage is required.

The above mentioned two methods only solve one problem that conventional electromagnetic bulging technology exhibits. In order to solve the two common problems of conventional tube electromagnetic bulging, this article proposes a method of electromagnetic bulging based on auxiliary coil as shown in Fig. 2(d). The bulging coil is that is placed inside the tube is of a height much greater than the tube height. The central part of the coil mainly provides radial electromagnetic force while the two ends of provide axial electromagnetic force that can increase the fluidity of the tube material and reduce the relative wall thickness thinning. However, because the radial electromagnetic force received by the tube is distributed in a concave profile, and the radial electromagnetic force at the end is too large, the forming amount of the end of the tube is greater than that of the middle of the tube. Therefore, in this article, upper and lower auxiliary coils are introduced in the periphery of the tube. The auxiliary coils are used to achieve tube electromagnetic compression, thereby weakening the magnetic field at the end regions of the tube, improving the stress on the tube side walls and improving the uniformity of tube axial deformation.

### III. ELECTROMAGNETIC-STRUCTURE COUPLING MODEL

In the electromagnetic forming process, there is a strong coupling of the electromagnetic field, structural field and temperature field. Thus, finite element analysis is used to precisely simulate the electromagnetic forming physical process [22], [23]. In this article, COMSOL software is used to establish two-dimensional axisymmetric model of the electromagnetic tube expansion process [24], [25]. Fig. 3 shows the electromagnetic forming simulation flow chart.

The developed model includes four modules:

1. **Global Ordinary Differential and Differential Algebraic Equations module**: used to simulate and analyze external circuits through solving set of differential equations [26], [27]. When there are no auxiliary coils, the equivalent circuit of the tube electromagnetic expansion is as shown in Fig. 4.
Based on Kirchhoff’s laws, the below equations can be derived:

\[
\begin{align*}
(R_0 + R)I_c + (L_0 + L + \frac{dL_w}{dt}) \frac{dI_c}{dt} + M_{m-w} \frac{dI_w}{dt} - U_c &= 0 \\
R_w I_w + L_w \frac{dI_w}{dt} + M_{w-m} \frac{dI_c}{dt} &= 0 \\
U_c &= U_0 - \frac{1}{C} \int_0^t I_c dt \\
I_{coil} + I_c - I_d &= 0 \\
I_d &= 0 & U_c \geq 0 \\
I_d &= \frac{U_c}{R_d} & U_c < 0
\end{align*}
\]  

(3)

With the proposed auxiliary coil, the equivalent circuit is modified as shown in Fig. 5. For this circuit, equation (3) is modified to:

\[
\begin{align*}
(R_0 + R + R_f)I_c + (L_0 + L + L_f + 2M_{f-m}) \frac{dI_c}{dt} + (M_{m-w} + M_{f-w}) \frac{dI_w}{dt} - U_c &= 0 \\
R_w I_w + L_w \frac{dI_w}{dt} + (M_{w-m} + M_{f-m}) \frac{dI_c}{dt} &= 0 \\
U_c &= U_0 - \frac{1}{C} \int_0^t I_c dt
\end{align*}
\]  

(5)

where \(U_c\) is the capacitor voltage, \(I_{coil}\) is the coil current, \(I_d\) is the crowbar circuit current and \(I_w\) is the induced eddy current in the tube.

(2) Magnetic field module: used to calculate the magnetic field and electromagnetic force distribution, and at the same time provides the electromagnetic force load for the solid mechanics module. Generally, the tube electromagnetic expansion employs a helical coil to apply an electromagnetic expansion force on the tube. Ignoring the influence of the asymptote in the coil, the cylindrical coil can be considered as a group of axially distributed closed rings. In this case, the bulging coil structure, the auxiliary coil, the workpiece and the electromagnetic field load source will be of axial symmetry and can be simplified into a two-dimensional axisymmetric model. The induced eddy current in the workpiece is dominated by the toroidal component, and the magnetic field can be expressed by Maxwell’s equations as below:

\[
\nabla \times \mathbf{H} = \mathbf{J} \quad (6)
\]

\[
\nabla \times \mathbf{E} \propto -\frac{\partial 
abla \times \mathbf{B}_z}{\partial t} + \nabla \times (\mathbf{v} \times \mathbf{B}_r) \quad (7)
\]

\[
\nabla \cdot \mathbf{B} = 0 \quad (8)
\]

\[
\mathbf{J}_\varphi = \gamma \mathbf{E}_\varphi \quad (9)
\]

where \(E\) is the electric field intensity; \(B\) is the magnetic flux density; \(v\) is the tube speed; \(J\) is the induced eddy current density; \(\gamma\) is the tube conductivity. The subscripts \(r\), \(\varphi\), and \(z\) denote the radial, hoop, and axial components of a vector, respectively.

(3) Solid Mechanics module: used to simulate the deformation process of a tube driven by the electromagnetic force. At the same time, the electromagnetic-structure coupling is realized by feeding back the deformation to the magnetic field module.

When the tube is stressed, it will comply with Newton’s law \(F = ma\), so the relationship between the force and displacement of the tube is as follows:

\[
\nabla \cdot \sigma + \mathbf{F} = \rho \frac{\partial^2 \mathbf{u}}{\partial t^2} \quad (10)
\]
where $\sigma$ is the stress tensor of the tube, $F$ is the bulk density vector of the electromagnetic force, $\rho$ is the tube density, and $u$ is the tube displacement vector.

Electromagnetic forming belongs to high strain rate deformation whose influence on the tube material needs to be considered. In this article, the Cowper-Symonds model is used to simulate AA5083-O tube, and its constitutive equation is as follows:

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

(11)

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

(12)

where $E$ is the Young’s modulus of the AA5083-O tube, $\sigma_{ys0}$ is the initial yield stress of the workpiece, $\sigma$ is the flow stress of the tube material during high-speed deformation, $m$ is the strain rate hardening parameter, $P$ is the viscosity, and $\sigma_{ys}$ is the quasi-static condition under flow stress as shown in (12), the constants $A$ and $B$ are 90.5MPa and 0.35 respectively. Generally, for aluminum material $P=6500$ and $m=0.25$[4].

(4) Moving grid module: used to update the air grid around the tube. In the model considered in this article, the outer boundary of the near-field air domain and the boundary of the coil domain are set as fixed boundaries; the far-field air domain and the coil domain are set as fixed grids and the near-field air domain and the tube domain are set as free deformation.

![FIGURE 6. Electromagnetic bulging of tube: (a) simulation results, (b) experimental results [13].](image)

In [13], this model is used to study the electromagnetic bulging of tube using concave driving coil. Simulation results were in good agreement with the experimental measurements as shown in Fig. 6. The difference between simulation and experimental results is only 3.18mm, and the tube forming height error does not exceed 2%. This validates the robustness of the of the simulation model which is also employed in this article to in investigate the performance of the proposed tube electromagnetic forming using auxiliary coils. The workpiece used in the forming process is AA5083-O pipe aluminum alloy of 37.5 mm radius, 2 mm thickness and 40 mm height. The detailed physical dimensions are as shown in Fig. 7 and the parameters of the external circuit are listed in Table 1. In addition, the auxiliary coil with 4 turns, height is 8mm, width is 4mm.

![FIGURE 7. Physical dimensions of the electromagnetic bulging using (a) traditional cylindrical coil, (b) proposed auxiliary coil.](image)

### TABLE 1. Parameters of the external circuit and workpiece.

| Symbol | Description | Value |
|--------|-------------|-------|
| $C_0$  | Capacitance | 320µF |
| $U_0$  | Discharge voltage | 3.2kV |
| $R_0$  | Line resistance | 35mΩ |
| $L_0$  | Line inductance (measured using LC bridge) | 12µH |
| $S$    | Copper wire cross sectional area | 2mm×4mm |

| Workpiece | |
|-----------|---|
| $r_{in}$  | Inner diameter | 75mm |
| $r_{out}$ | Outer diameter | 79mm |
| $H_{w}$   | Height | 40mm |
| $\rho$    | Density | 2700kg/m³ |
| $\sigma$  | Electrical Conductivity | 3.03e7S/m |
| $\gamma$  | Poisson's ratio | 0.33 |
| $E$       | Young’s modulus | 70GPa |
| $\sigma_{ys0}$ | Initial yield stress | 32.6MPa |

### IV. SIMULATION RESULTS

The pulse current is the source of the magnetic field whose distribution is mainly determined by the coil geometry. In this
section, the effect of coil geometrical parameters on the electromagnetic force, deformation behavior and relative wall thickness reduction of the tube is investigated. A comparison of the electromagnetic forming performance of the traditional cylindrical coil and the proposed auxiliary coil is also provided.

A. RADIAL ELECTROMAGNETIC FORCE AND DEFORMATION BEHAVIOR OF PIPE FITTING

The auxiliary coil used in the analysis is of 8mm height, 53mm inner ring radius and 57mm outer ring radius. In order to analyze the radial electromagnetic force and the deformation behavior of the tube, three coil geometrical parameters are changed in specific ranges and the effect of each parameter change is investigated while all other parameters are kept constant. Investigated parameters are: -distance between the auxiliary coil and the tube ($H_i$) is varied in the range 11mm to 18mm with 1mm step change, -distance between the upper and lower auxiliary coils ($H_o$) is changed in the range 16mm to 24mm with 1mm step change, and -the height of the bulging coil ($H_d$) is changed from 48mm to 68mm in a step length of 4mm.

1) EFFECT OF $H_i$

Fig. 8(a) shows the effect of various distances between the auxiliary coils and the pipe on the radial electromagnetic force. It can be seen that the radial electromagnetic force is of a concave profile with a minimum value at the axial center of the tube (20 mm). The radial electromagnetic forces at both ends of the tube are almost of equal magnitudes and it decrease by increasing $H_i$. The radial electromagnetic force at the middle of the tube also decreases gradually with the increase of $H_i$. Therefore, changing $H_i$ can effectively change the radial electromagnetic force profile on the tube.

Fig. 8(b) shows the effect of changing $H_i$ on the deformation behavior of the tube. It can be observed that with the increase of $H_i$, the forming contour of the pipe in the axial direction changes from upper convex to lower convex profile. At a specific value of $H_i$ (14 mm in this analysis), the pipe fitting is evenly bulged.

2) EFFECT OF $H_o$

Fig. 9(a) shows the effect of the distance between the upper and lower auxiliary coils on the radial electromagnetic force. Similar to the above case study, it can be seen that as the distance between the auxiliary coils increases, the radial electromagnetic force on the middle section of the tube gradually decreases.

Fig. 9(b) shows the influence of changing $H_o$ on the deformation behavior of the tube. In contrary with the above case study, results show that with the increase of $H_o$, the tube forming contour in axial direction changes from lower convex to upper convex. With other structural parameters unchanged, there is an optimum auxiliary coil spacing (20 mm in this case) at which the pipe fitting is evenly bulge

3) EFFECT OF $H_d$

Fig. 10(a) shows the effect of the bulging coil height on the radial electromagnetic force. It can be seen that as the coil height increases, the radial electromagnetic force on the end of the tube increases, while the electromagnetic force on the middle section decreases. Fig. 10(b) shows that with increase of $H_d$, the change of the forming contour of the tube in the axial direction is quite similar to that of Fig. 8(b), and the optimal bulging coil height is 56mm.

The above analysis shows that a proper physical structure design of the proposed electromagnetic forming using auxiliary coils improves the radial distribution characteristics of the electromagnetic force, thereby improving the uniformity of the axial deformation of the tube. It is worth noting that for a specific tube, optimum geometric parameters of the proposed auxiliary coils need to be calculated to obtain more uniform axial deformation. In this article, the optimum values of $H_i$, $H_o$, and $H_d$ are 14mm, 20mm, and 56mm; respectively.
FIGURE 9. Effect of the distance between upper and lower auxiliary coils on the (a) radial electromagnetic force; (b) deformation behavior.

### B. RELATIVE WALL THICKNESS REDUCTION

In this section, the thickness of the central wall of the tube and the axial electromagnetic force distribution under different coil geometric parameters are investigated. As the bulging radius of the pipe becomes larger, the pipe wall thickness reduction will increase. Therefore, this article introduces the relative wall thickness reduction index $R_w$, which is defined as the reduction in the wall thickness of the pipe divided by the bulging amount. Fig. 11 shows the effect of various values of $H_i$ on the axial electromagnetic force and relative wall thickness reduction while Figs. 12 and 13 respectively show the effects of $H_o$ and $H_d$ variations on the same two parameters. In these figures, the left y-axis (axial electromagnetic force, 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 ($R_w$, shown in red colour) refers to the reduction of the tube relative 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). With the increase of the axial electromagnetic force, the axial fluidity of the material is enhanced, so that the material is filled in the bulging and thinning area in time, and the relative wall thickness reduction at the center of the pipe is suppressed.

The results show that the axial electromagnetic force decreases with the increase of $H_i$ while it increases with the increase of $H_o$ and $H_d$. The results also show that with the increase of $H_o$ and $H_d$, the thinning of the relative wall thickness gradually decreases, and with the increase of $H_i$, the thinning of the relative wall thickness gradually increases. This indicates that the axial electromagnetic force can be increased and the wall thickness reduction of the tube can be suppressed by a proper adjustment of the system physical dimensions.
C. COMPARATIVE ANALYSIS

In order to validate the advantages of the proposed electromagnetic bulging topology, a comparative analysis with the traditional cylindrical coil is conducted in terms of axial and radial electromagnetic forces and the tube deformation behavior. Table 2 shows the geometric parameters of the analyzed cylindrical and auxiliary coils. As mentioned above, the workpiece is an AA5083-O aluminum alloy tube with a length of 40 mm, a diameter of 37.5 mm, and a thickness of 2 mm. At the same time, for accurate comparison of pipe bulging uniformity, the discharge voltage is set to 2.66kV when using the traditional helical coil and 3.2kV when using the auxiliary coils to ensure the maximum deformation of the two pipes using the two loading methods is the same.

| TABLE 2. Geometric parameters of the analyzed cylindrical and auxiliary coils (in mm). |
|-------------------------------------------------|
| Cylindrical coil | Height | Inner diameter | Outer diameter |
| Bulging coil | 40 | 30 | 34 |
| Auxiliary coil | 56 | 30 | 34 |
| Upper auxiliary coil | 8 | 53 | 57 |
| Lower auxiliary coil | 8 | 53 | 57 |

Fig. 14 shows the distribution of the radial electromagnetic force density on the tube when the conventional and proposed driving coils are utilized. Apparently, the maximum amplitude of the radial electromagnetic force is located at the axial middle region of the tube when the conventional cylindrical 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 auxiliary coil is used. Compared with the traditional coil structure, the proposed structure provides more axial electromagnetic force, increases the axial flow of the material and suppresses
the relative wall thickness reduction during the deformation process as shown in Fig. 15.

\[ D_r \] which represents the axial length less than or equal to 96% of the maximum deformation amount is calculated. As shown in Fig. 17, \( D_r \) is 6.9mm when the traditional cylindrical coil loading is used while it is 35.1mm when the proposed auxiliary coil loading is employed. This proves the effectiveness of the proposed electromagnetic bulging method using auxiliary coil to enhance the axial deformation uniformity of the tube.

In order to compare the effectiveness of the proposed method with the results reported in [13], [14], Table 3 lists the percentage improvement of the tube bulging uniformity using different coil structures along with the relative wall thickness reduction of the tube. It can be observed that with the use of auxiliary coil as proposed in this article, the axial uneven tube bulging and tube wall thickness reduction can be improved simultaneously.

### TABLE 3. Comparison of different coil forming effects.

|                     | Evenness (%) | Relative wall thickness reduction |
|---------------------|--------------|----------------------------------|
| Concave coil [13]   | 171.38       |                                  |
| Double coil [14]    | 0.034        |                                  |
| Proposed auxiliary coil | 408.7       | 0.01661                          |

### V. CONCLUSION

Aiming at overcoming the current issues of the conventional tube electromagnetic forming, this article proposes the use of auxiliary upper and lower coils to lengthen the bulging coil and hence increasing the axial electromagnetic force. This topology can effectively reduce the thinning of the tube relative wall thickness and at the same time, weaken the deformation of the tube end and thus achieving improved axial deformation uniformity. Results show that when the proposed auxiliary coil loading is used, the radial electromagnetic force profile is of concave distribution that weakens the deformation of the tube end and facilitates even deformation.
in the axial direction. At the same time, the axial electromagnetic force can increase the axial fluidity of the pipe material, so that the material can be filled in the forming and thinning area in time, which can effectively suppress the relative wall thickness reduction of the pipe. For the same tube internal expansion, the auxiliary coil loading method can improve the uniformity of the tube by nearly 5 times the traditional coil loading. Obviously, the auxiliary coil loading electromagnetic forming proposed in this article can solve the problems of tube forming uniformity and relative wall thickness reduction to a certain extent. Future experimental validation is necessary to validate the feasibility of the proposed method for various practical applications.

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