Tube Electromagnetic Free Bulging Based on Internal Negative-External Positive Three-Coil System

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ABSTRACT
Controlling the direction and profile of the electromagnetic force (EMF) is a key of improving the tube axial-uniformity and wall thickness during the electromagnetic forming process. In this regard, this article proposes a new tube electromagnetic-bulging topology using internal negative-external positive three-coil system. This structure is aimed at realizing effective bidirectional loading of axial and radial EMFs on the tube. An electromagnetic-structure coupling two-dimensional model is proposed to study the effect of the coil structure on the EF profile, bulging profile and the tube wall-thickness. The performance of the proposed method is compared with the traditional method through several performance metrics that include the electromagnetic force distribution cloud map, the tube bulging uniformity and its wall thickness. Numerical simulation results show that by changing the coil structure, the radial EMF profile can be effectively enhanced, and the free bulging contour of the tube can be further regulated. The additional axial EMF due to the proposed structure can promote the axial-flow of the material, thereby suppressing the reduction in the tube wall-thickness which is unavoidable using the traditional method. In comparison to the traditional single-coil system bulging, the maximum axial uniformity range of the tube is increased from 6.5mm to 35.2mm, and the wall thickness of the most severely thinned area is increased from 1.43mm to 1.77mm which verifies the effectiveness of the proposed method.

INDEX TERMS
Bulging uniformity, electromagnetic forming, electromagnetic force distribution, three-coil system, wall thickness reduction.

I. INTRODUCTION
The use of lightweight alloy materials has been of a great significance to the rapid development of aerospace, transportation and large machinery [1]–[5]. The main issues associated with the light alloy materials include its low forming properties at room temperature, poor drawability, easy tearing and springback, which complicates the traditional forming processing techniques for such materials [6]. As such traditional forming methods have been replaced by electromagnetic-based techniques that employ EMFs to accomplish the forming-process of alloy materials [7]–[9]. The electromagnetic-forming can effectively enhance the materials’ plastic deformation and upturn its forming limit up to 10 times, enhance the stress-distribution on the metal objects and the surface quality of the final product [10]–[16]. The workpiece-deformation homogeneity and the amount of wall-thickness reduction have been among the sustained subjects that researchers have paid attention to [17]–[19]. In order to improve the homogeneity of the axial-deformation of formed tube, Cui et al. [20] incorporated the idea of progressive forming into the traditional electromagnetic bulging process. Ref. [21] proposed a uniform pressure multilayer rectangular coil with a metal U-shaped...
external channel to provide a relatively even induced current and achieve a uniform electromagnetic force distribution on the workpiece. Ref. [22] proposed a 3D numerical simulation model of a magnetic-structure field coupling to study the metal tube uniformity under electromagnetic bulging. The model yielded simulation results that are confirmed by experimental analysis. Ref. [23] introduced a concave coil structure to load tube in order to deteriorate the radial EMF acting on the central section of the tube to enhance its uniformity. In [24] a field shaper is utilized to study the main parameters affecting the joint strength of the tubular member produced by the electromagnetic compression. Results show that different parameters have a significant impact on the strength and failure characteristics of the joint. At the same time, a field shaper can be used to obtain a uniform radial displacement. In order to reduce the substantial decrease in the wall thickness of the formed workpiece, Ref. [25] presented a triple-coil based electromagnetic forming system. Ref. [26] proposed electromagnetic free bulging based on double-coil axial compression tube. When the plate is deeply formed, the material flow is reduced in the radial-direction which results in a severe reduction in the plate’s wall-thickness and makes it more prone to breakage. Ref. [27] proposed an electromagnetic forming method for shaft-diameter bidirectional loading to effectively promote the radial flow of the plate and hence improving the forming performance.

The above methods suggest that by changing the relative position of the driving coils and / or its structure, the uniformity of the workpiece can be effectively improved and the decrease in the workpiece wall-thickness can be suppressed. However, an effective topology to simultaneously solve the two issues of tube deformation uniformity and wall thickness reduction has not been given much attention.

To simultaneously increase the forming homogeneity of the tube and suppress the wall-thickness reduction, this article presents an electromagnetic-forming topology based on inner negative-outer positive three-coil system tube. Effectiveness of the proposed topology is examined using an electromagnetic structural finite element analysis for the tube wall displacement in electromagnetic bulging as elaborated below.

II. TRADITIONAL AND PROPOSED SYSTEMS
A. TRADITIONAL SINGLE-COIL SYSTEM
The tube free bulging system as depicted in Figure 1 includes charging system, capacitor bank, air switch, bulging coil and crowbar resistance [28], [29]. The capacitor bank is initially fully charged through the charging circuit. The capacitor stored energy is then discharged through the air switch to apply a pulsed current into the bulging coil. According Lenz’s law, this will generate an induced eddy current in the metal tube surrounding the bulging coil [30], [31]. Large electromagnetic force is produced as a result of the interaction between the induced eddy current and the generated magnetic flux. This force accelerates the tube at a high speed to achieve free bulging [32].

In the traditional electromagnetic process, the bulging-coil is located coaxially within the metal tube that should have a height more than or equal to that of the coil as shown in Figure 2. In this figure, $J_\phi$ is the circumferential component of the induced eddy-current density while $B_z$ and $B_r$ represent the magnetic flux densities in the axial and radial directions. This topology comprises some drawbacks. The radial electromagnetic force component is large while there is almost no axial force component. This will accelerate the tube outward and produce free expansion, which signifies the reduction in the tube-wall. Furthermore, the radial electromagnetic force distribution along the tube is uneven as it is large in the middle and small at both ends as shown by the red arrows in Figure 2. Hence, the forming amount at the axial center of the tube becomes larger than that at both ends, resulting in uneven forming and reduced mechanical strength of the tube.

B. PROPOSED THREE-COIL SYSTEM
To overcome the existing issues associated with the tube-bulging using traditional single-coil system simultaneously, a new tube electromagnetic-bulging topology through the use of internal negative-external positive three-coil system as shown in Figure 3. In this topology, a bulging coil (outer ring coil) with a more height than the tube is introduced. The middle section of this coil is mainly producing radial-EMF while the two ends of the coil produce inward axial-EMF to generate axial compression as shown by the red arrows.
in Figure 3. Therefore, while the metal workpiece is bulging under the action of radial electromagnetic force, axial compression also takes place due to the action of the axial-EMF. This axial-compression facilitates the workpiece material to reach the bulging zone in time. However, because the radial-EMF is of concave-profile, the bulging amount close to the ends of the tube is greater than the deformation amount of the middle section. Therefore, an inner ring coil with a reverse pulse current is utilized within the expanded coil as shown in Figure 3. The reverse pulse magnetic field generated by the inner ring coil acts to weaken the magnetic field at the ends of the tube, thus enhancing the radial EMF profile and realizing homogenous axial-deformation uniformity over the entire tube.

With the system shown in Figure 3, the tube is subjected to a simultaneous bidirectional loading of radial and axial EMFs that can be calculated from:

\[
F_r = (J_{\phi_1} + J_{\phi_2}) \times (B_{z1} + B_{z2}) \tag{1}
\]

\[
F_z = (J_{\phi_1} + J_{\phi_2}) \times (B_{r1} + B_{r2}) \tag{2}
\]

where, subscript 1 represents the parameters related to the bulging coil (outer ring coil) and subscript 2 indicates the parameters associated with the inner ring.

III. FINITE ELEMENT ANALYSIS MODEL AND SYSTEM PARAMETERS

The free bulging of the tube is a complex transient process, which involves strong coupling between various fields which can be precisely simulated using finite element analysis [29], [32]. COMSOL finite element analysis tool is used to simulate a 2D-axisymmetric model of the electromagnetic-forming process [32].

The specific grid division is shown in Figure 4. In the developed model, the boundary of the far-field region as shown in Figure 4 is assumed to be stationary with fixed grids. On the other hand, the deformation area of the tube is set as free deformation grids that change with the bulging of the tube.

The physical structure of the developed two-dimensional axisymmetric electromagnetic-structure model is shown in Figure 5. In this model, the bulging coil employed for the traditional method comprises 2 layers of 10 turns each and is of inner / outer radii 30mm / 34mm. The bulging coil employed for the proposed system contains 2 layers of 16 turns each and is of similar inner / outer radii of the above coil. The additional proposed upper inner coil has 2 layers of 2 turns each with 25mm inner radius and 29mm outer radius. All coils are made of uniform copper-wires of cross-sectional area 2mm × 4mm. The height of the bulging coil \(H_o\) and the spacing between the upper- and lower-inner coils \(H_d\) are investigated in the simulation results below. The used AA5083-O aluminum alloy tube is of 40mm height, 37.5mm inner radius and 39.5mm outer radius.

As shown in Figure 1, the equivalent discharge circuit includes a capacitor bank \((C)\) with a freewheel diode and a crowbar equivalent resistance \(R_d\), line inductive impedance \((R_1, L_1)\), bulging coil \((R_c, L_c)\), and the tube equivalent parameters \((R_w, L_w)\). These parameters are given in Table 1.
FIGURE 5. Schematic for geometric parameters: (a) the traditional single-coil system, (b) proposed system.

TABLE 1. Equivalent discharge circuit parameters.

| Symbol | Description | Value       |
|--------|-------------|-------------|
| C      | Capacitance | 320μF       |
| $U_0$  | Initial voltage | 2.8kV   |
| $R_l$  | Line resistance | 35mΩ     |
| $L_l$  | Line inductance | 12μH     |
| $R_d$  | Crowbar resistance | 0.287Ω |

After adding the inner coil, and based on Kirchhoff’s law, the discharge circuit equations are [28]:

\[ U_c = U_l + U_{\text{coil1}} + U_{\text{coil2}} \] (3)

\[ I_{\text{coil}} + I_c - I_d = 0 \] (4)

where $U_c$ is the coil voltage that has initial value of $U_0$, $U_l$ is the line voltage of the equivalent discharge circuit, $U_{\text{coil1}}$ and $U_{\text{coil2}}$ are the voltages of the outer and inner bulging coils.

The circuit specific parameters can be calculated as below:

\[ U_c = U_0 - \frac{1}{C} \int_0^t I_c \, dt \] (5)

\[ U_l = R_0 I_{\text{coil}} + L_0 \frac{dI_{\text{coil}}}{dt} \] (6)

\[ U_{\text{coil1}} = R_1 I_{\text{coil}} + L_{c1} \frac{dI_{\text{coil}}}{dt} + M \frac{dI_w}{dt} \] (7)

\[ U_{\text{coil2}} = R_2 I_{\text{coil}} + L_{c2} \frac{dI_{\text{coil}}}{dt} + M \frac{dI_w}{dt} \] (8)

\[ \begin{cases} I_d = 0 & U_c \geq 0 \\ I_d = \frac{U_c}{R_d} & U_c < 0 \end{cases} \] (9)

where $I_d$ is the diode current flowing through the freewheeling loop, $M$ is the mutual-inductance between the metal tube and coil.

The parameters of the employed AA5083-O aluminum alloy tube are shown in Table 2. The dynamic motion of the tube is expressed by the following equation:

\[ \rho \frac{\partial^2 u}{\partial t^2} - \nabla \cdot \sigma = F \] (10)

where $u$ is the displacement-vector, $\rho$ is the mass-density, $\sigma$ is the stress-tensor, and $F$ is the volume-density vector of the electromagnetic force.

TABLE 2. AA5083-O material parameters.

| Symbol | Description       | Value       |
|--------|-------------------|-------------|
| $\rho$ | Mass density      | 2700 kg/m³ |
| $\sigma$ | Conductivity    | 3.03e7 S/m |
| $\gamma$ | Poisson ratio | 0.33       |
| $E$    | Youngs modulus   | 70 GPa      |
| $\sigma_{\text{yr}}$ | Initial-yield-stress | 32.6 MPa |

The constitutive equation is a description of the macro-mechanical behavior of the material which reflects the relationship between the flow stress and the material processing parameters. Cowper-Symonds model is widely used to describe the material behavior under high strain rate [32].

\[ \sigma = \sigma_{qs}[1 + (\frac{\varepsilon}{p})^k] \] (11)

where $\sigma$ is the stress under high strain rate, $\sigma_{qs}$ is the stress under quasi-static condition, and $\varepsilon$ is the strain rate. For aluminum alloy materials, $p$ and $k$ are usually 6500s^{-1} and 0.25, respectively.

In [23], this model is used to simulate the electromagnetic bulging of tubes based on concave driving coils. The numerical simulation results were found in good agreement with the experimental results, and the difference in $L$ value does not exceed 0.5mm, as shown in Figure 6. This verifies the correctness of the simulation results and the validity of the simulation model. The same model is employed in this paper to study the tube electromagnetic bulging based on new driving coil topology; namely internal negative-external positive three-coil system.

IV. SIMULATION RESULTS AND DISCUSSION

This section investigates the influence of the proposed inner and outer coils structural parameters on the radial-EMF, bulging profile and tube wall-thickness. Also, performance comparative analysis in terms of tube wall thickness and forming uniformity with the conventional single-coil system is conducted.
A. TUBE UNIFORMITY ANALYSIS

To explore the impact of the coil design parameters on the EMF and the tube bulging profile, the height of the bulging-coil $H_o$ is varied from 52mm to 76mm, with a 4mm step-change while the separation between the upper- and lower-coils $H_d$ is varied in the range 45.6mm - 56.6mm in a 2mm step. In both cases, the coil cross sectional area is kept unchanged.

Figure 7(a) shows the influence of $H_o$ on the radial EMF profile while maintaining $H_d$ at its initial value. It can be observed that with the increase of $H_o$, the radial-EMF distribution changes from convex to concave and it gradually increases at the tube’s ends while decreases at the central section. Figure 7(b) shows the effects of $H_o$ variation on the tube bulging profile in the axial direction. It can be seen that with the increase of $H_o$, the bulging behavior of the tube varies from upward-convex to downward-convex shape. When the height of the bulging-coil is small, the magnetic field intensity at the middle of the tube is the strongest, resulting in the largest deformation in this area. When the height of the bulging coil is increasing, the EMF at the ends of the tube is intensifying, which causes the forming volume of the end part to be much larger than that of the middle part. Results of Figure 7 reveal that the best bulging performance is achieved when $H_o$ is set at 64mm.

Figure 8(a) depicts the influence of the upper- and lower-coils spacing on the radial-EMF when $H_o$ is kept at its initial value. As can be observed, the EMF in the middle of the tube experiences a small variation. However, with the growth of $H_d$, the EMF at the ends of the tube gradually increases with the same amplitude. Figure 8(b) displays the impact of $H_d$ variation on the bulging profile of the tube. From the figure, one can see that when the coils spacing is small, the bulging amount of the middle part is greater than that of the tube’s ends due to the relatively large EMF at the two ends of the tube when compared with that at the middle section. When the separation distance becomes large, the increased magnetic field at the ends of the tube results in excessive end forming. From Figure 8, the optimum value of $H_d$ that results in the best tube bulging uniformity is 51.6mm.

B. TUBE WALL-THICKNESS ANALYSIS

In this analysis, the tube center is selected as the research node to investigate the axial-EMF and the wall-thickness performance. As the bulging profile becomes larger, the tube’s wall thickness becomes thinner. Therefore, for accurate comparative analysis of the wall-thickness performance under different bulging profiles, a relative wall-thickness reduction-index $R_w$ is calculated. $R_w$ is defined as the tube wall thickness reduction divided by the tube bulging amount. Figures 9 and 10 show the influence of $H_o$ and $H_d$ on $R_w$, respectively. The left y-axis in both figures represents the maximum value of the axial-EMF $F_z$, while the right y-axis represents $R_w$. It can be seen that all the axial electromagnetic forces are positive, which means the tube is compressed in the axial-direction. With the increase of $H_o$, the axial-EMF increases from $1.63 \times 10^9$N/m$^3$ to $4.35 \times 10^9$N/m$^3$, while the increase of $H_d$ changes the axial electromagnetic force from...
3.38 $\times$ 10$^9$ N/m$^3$ to 3.68 $\times$ 10$^9$ N/m$^3$. The extra EMF promotes the axial-flow of the tube material and aids in filling it into the bulging and thinning areas so that preventing the thinning phenomena of the tube wall-thickness which is the main issue of the traditional electromagnetic forming system.

C. COMPARISON WITH CONVENTIONAL METHOD

In this section, the proposed and the traditional electromagnetic forming topologies are compared in terms of the work-piece uniformity and wall-thickness. Based on the above results, the radial electromagnetic force is mainly used to generate radial bulging of tube. Therefore, the radial-EMF profile using the two loading systems is obtained as shown in Figure 11. In this figure, the X-axis is the axial position of the tube, the Y-axis is the time, and the Z-axis is the radial-EMF. Figure 11(a, b) show that when the traditional single-coil loading system is utilized, the radial-EMF presents a convex distribution profile and the middle part of the tube is exposed to the largest EMF with smaller force on the tube’s ends. At discharging time of 200 $\mu$s, the bulging of the metal tube by the radial-EMF ends.

On the other hand, Figure 11(c-d) depicts that when the new three-coil system is used for loading, the radial-EMF presents a concave profile with an amplitude at the ends of the tube greater than that at the middle. In this case, the bulging ends at $t = 250 \mu$s, which is attributed to the effect of the increased pulse-current width when the inner coil is added. Results reveal that the proposed system can improve the distribution profile of the radial-EMF and enhance the homogeneousness of the bulging profile of the tube.

In addition, the proposed three-coil system also improves the axial electromagnetic force distribution, as shown in Figure 12. When the conventional single-coil system is used for loading, the maximum axial electromagnetic force is 1.2 $\times$ 10$^9$ N/m$^3$ and it does not compress outward in the area close to the middle of the tube. Whereas when the proposed three-coil system is used for loading, the maximum axial-EMF increases 3-times and reaches 3.6 $\times$ 10$^9$ N/m$^3$ which promotes the axial flow of the tube material. In addition, there is no outward axial-EMF at the middle of the tube.
Further, the distribution of the coil current under different loading modes is shown in Figure 13. It can be seen that the peak current of the traditional coil is 8.865kA. The outer loop driving coil peak current is 7.957kA, which is the same peak current of the inner loop driving coil but in opposite direction.

Fig. 14 shows the radial displacement of the tube under the traditional and proposed loading systems. With the proposed system and when the maximum expansion amount is consistent, the tube almost expands uniformly with an amount of 10.2mm. However, with the conventional single-coil system, the maximum expansion of the middle part of the tube is 10.2mm, while it is only 1.2mm at the end of the tube. This expansion effect is closely related to Fig. 11(a), because the radial-EMF of the central section of the tube is larger than that of the ends part.

In order to compare the uniformity of free expansion of tube, the expansion effect is further analyzed. Fig. 15 shows
a two-dimensional plot for the final expansion of the tube under the two investigated loading systems. A maximum uniform range $D_r$; the axial distance of the expansion less-than or equal-to the overall maximum expansion is calculated for the two systems. This value is only 6.5mm when the conventional single-coil loading system is employed, while it increases substantially to 35.2mm when the new three-coil system is used which reveals an improvement of axial uniformity by 5.43 times when compared with the traditional system.

Figure 16 depicts the wall-thickness at the end of the free bulging of the tube. The initial tube wall thickness is 2mm. When the conventional single-coil system is utilized, the wall-thickness close to the tube ends is severely reduced to reach a final value of 1.43mm while it reaches 1.77mm when the proposed system is employed.

V. CONCLUSION
To improve axial homogeneousness profile and suppress the thinning of the wall-thickness after the free bulging of the tube, a three-coil loading system is presented in this paper. The system is designed to provide reasonable and simultaneous radial- and axial-EMFs on the tube so that the tube can realize bidirectional loading. Numerical analysis shows that by changing the coil structural parameters, the distribution of the radial-EMF can be effectively enhanced, and the free bulging contour of the tube can be further regulated. The additional axial-EMF can suppress the tube’s wall-thickness reduction. Compared with the convex radial-EMF profile provided by the conventional system, the concave radial-EMF distribution produced by the proposed system facilitates the uniform expansion of the tube, and increases the uniform expansion by 5.43 times. Results also show that by extending the height of the bulging-coil, tube’s wall
thickness is increased from 1.43mm, in case of traditional single coil to 1.77mm when the proposed three-coil system is used. The authors will carry out follow-up experiments based on the obtained simulation results to verify the feasibility of the proposed system and the effectiveness of the simulation model.

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