A Flexible and Economic Method to Improve the Ability of Electromagnetic Flanging for Tubes

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Abstract

In recent years we have seen the rapid development of electromagnetic flanging of tubes, which uses coils to generate electromagnetic forces to achieve the deformation with high speed but without contact. However, the electromagnetic force decays rapidly with the increase of distance, resulting in strict requirements of geometrical matching between the coils and the tubes. Usually, new coils should be fabricated for tubes with new sizes, which is inconvenient and uneconomical. Therefore, a more flexible and economical method is proposed in this article, which introduces a solenoid field shaper into the existing electromagnetic flanging system. By adjusting the structure and the position of the field shaper, the distribution of electromagnetic forces can be reshaped.
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to form tubes with various sizes, without changing the coil, whose cost is much higher than a field shaper. The principle of this method is introduced in detail. Then an electromagnetic-structure coupled finite element simulation model is established to calculate the forming process. The results show that when forming an A1060-O aluminum alloy tube with an inner diameter of 110mm, the discharge voltage can be tuned down from 8.9kV, without field shaper, to 7.4kV, with field shaper. That means the energy consumption of the system can be saved by 31%, and the manufacturing process of the field shaper is simpler than that of the forming coil. What’s more, when forming tubes with different sizes, the new method shows higher effectiveness, greater flexibility, and lower cost than the traditional way.

Keywords: Electromagnetic flanging, Field shaper, Tube, Electromagnetic force, Flexibility.
1. Introduction

Flanging of metal tubes is a common processing technology in the industry, and the parts have usually been used in manufacturing fields such as automobiles, aerospace, and instruments [1]. When flanging metal tubes with traditional technology, the process is very cumbersome and requires multiple working procedures. However, the electromagnetic flanging is a more effective method to achieve the flanging of aluminum alloy tubes. The electromagnetic flanging process uses pulse electromagnetic forces, which are non-contact. The basic principle of electromagnetic flanging is Lenz's law. A time-varying magnetic field induces an eddy current in the tube that resists the change of the magnetic field, then the interact between each other generates a huge electromagnetic force instantly, which causes the tube to turn over. It has a series of advantages such as faster forming speed, higher forming limit, and less spring back [2]. What’s more, some specific workpieces can only be completed by electromagnetic flanging, so many scholars have been carrying out unremitting research on electromagnetic flanging [3].

Li et al. [4] performed electromagnetic flanging on the end of the tube. The test results show that the limit flanging coefficient of the electromagnetic flanging can be increased by 17%–26% when compared with the ordinary stamping and flanging process. Li et al. [5] also studied the influence of coil length and its position on electromagnetic bulging by using the loose coupling method. Xiong et al. [6] proposed the electromagnetic flanging of the tube which is based on the attractive
electromagnetic force generated by the improved double coils. However, the new coils should be fabricated for tubes with new sizes, in all the above methods, which is inconvenient and uneconomical.

The reason for above problem is that, in the process of flanging the tube, the electromagnetic force decays rapidly with the increase of distance, resulting in strict requirements of geometrical matching between the coils and the tubes. For tubes with larger inner diameters, larger shaped coils need to be selected. On the one hand, new coils should be fabricated for tubes with new sizes. For different tube sizes, different coils need to be replaced, which is inconvenient. On the other hand, the winding process of the coil is very complicated, and frequent replacement of the coil will increase the cost.

In order to solve these problems, a flanging forming method of the tube with a field shaper is proposed in this article. A solenoid field shaper is introduced into the existing electromagnetic flanging system. By adjusting the structure and the position of the field shaper, the distribution of electromagnetic forces can be reshaped to form tubes of various sizes, without changing the coil, whose cost is much higher than a field shaper. The field shaper is a commonly used auxiliary accessory with low cost and has the function of extending the service life of the coil. To test this method, an electromagnetic-structure coupling finite element simulation model was established. A series of simulations have been done with this model and their results are shown below.
2. Principle and Design

2.1 Traditional electromagnetic flanging

The traditional electromagnetic flanging system of the tube mainly includes a charging system, a capacitor power supply, an air switch, a coil, a tube, and a fly-wheel circuit. Its principle is shown in Fig.1(a). First, the charging system charges the capacitor banks. After the charging is completed, the stored energy is released to the coil through the air switch, thereby generating an instantaneous pulse current. The current generates a strong pulsed magnetic field, which in turn excites an induced eddy current in the tube. The interaction between the induced eddy current and the magnetic field generates a strong repulsive force, which drives the tube to deform, which can be expressed as [7]

\[ F = J_e \times B \]  

(1)

Where \( B \) and \( J_e \) are magnetic flux density of tube and eddy currents density. Electromagnetic force can be decomposed into axial and radial component in the analysis of an electromagnetic flanging process [8], which are called radial Lorentz force and axial Lorentz force, and they are determined by [9]:

\[ F_r = J_e \times B_r \]  

(2)

\[ F_z = -J_e \times B_z \]  

(3)

Where \( B_z \) and \( B_r \) are the radial component and the axial component of the magnetic flux density respectively.

2.2 Electromagnetic flanging with a field shaper

The field shaper is a commonly used auxiliary accessory to strengthen the magnetic field in a specific area during the electromagnetic forming process. It mainly uses the
skin effect and the unique structure to cooperate with each other to transmit the induced eddy current of the coil, so as to change the position and shape of the magnetic field generated by the forming coil. As a matter of fact, the structure of the field shaper is a rotating conductor, which is generally composed of high-conductivity metal materials, such as copper and aluminum. As shown in Fig.2, this article uses an solenoid field shaper, the material of which is the same as the forming coil. The structure of the solenoid field shaper has two inner and outer surfaces. The height of the inner surface is much larger than that of the outer surface, and there is an air gap in its longitudinal direction. According to the literature, the influence at the air gap can be ignored, so the three-dimensional model is simplified to a two-dimensional axisymmetric model in this article [10].

When introduced into the tube flanging forming system, the field shaper is located between the coil and the tube, as shown in Fig.1(b). Due to the skin effect and Lenz’s law, this induced eddy current flows to the outer surface of the field shaper from the axial slot [11]. So, the current direction is the same as which in the coil. Accordingly, the energy of the forming coil is transferred from the forming coil to the workpiece, equivalent to shorten the distance. The skin depth is determined by

$$\Delta = \frac{1}{\sqrt{\pi \sigma \mu f}}$$

(4)

where $\mu$ is the permeability, $\sigma$ and $f$ are the conductivity and frequency of current.

The design principle of field shaper in electromagnetic flanging is similar to it. The induction vortex of forming coil in metal workpiece is mainly concentrated in the
surface area of the workpiece. Thus the design idea of field shaper comes from this.

Fig. 1. Schematic diagram of electromagnetic flanging system: (a) without field shaper; (b) with field shaper
Fig.2. Structure diagram of solenoid field shaper

The simplified diagram of the existing electromagnetic flanging process is shown in Fig.3(a). If a larger tube (Tube2) is to be formed, a larger forming coil (Coil2) needs to be replaced as shown in Fig.3(b), which is undoubtedly more complicated. Based on this, this article adds a field shaper to the system as shown in Fig.3(c). Without changing the coil, the magnetic field configuration generated by the forming coil is changed by the field shaper, so that the magnetic field lines are concentrated on the area to be flanged, and the flanging effect of the tube is optimized.

Fig.3. Scheme flow chart

3. Simulations

The main purpose of this article is to analyze and compare the flanging effects of different sizes of tubes. Thereby, three tubes with different inner diameters are selected for numerical simulation. Numerical simulation is one of the indispensable methods in the study of the electromagnetic forming process. In this article, based on COMSOL, the electromagnetic structure coupled FEM simulation model of the tube was built, as shown in Fig.4, to simulate the plastic deformation process of aluminum alloy tubes in
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a time-varying electromagnetic field.

Symmetry axis

38.6

Field shaper
Coil
Tube

Unit: mm

Fig. 4. The geometry of numerical simulation

3.1 Circuits

The discharge circuit is the "engine" of the electromagnetic flanging technology, which provides the transient change of discharge current for the forming coil. For the moment, the most common RLC discharge circuit is based on a capacitor. The equivalent circuit is shown in Fig.5.

Fig. 5. Equivalent schematic diagram without field shaper
The discharge circuit equation with freewheeling loop is as follows:

\[ U_c = (R_c + R_e) I_{coil} + L_c \frac{dI_{coil}}{dt} + (\frac{dL_c I_{coil}}{dt} + \frac{dMI_w}{dt}) \]  

(5)

\[ I_{coil} + I_c - I_d = 0 \]  

(6)

\[ U_c = U_0 + \frac{1}{C} \int I_c dt \]  

(7)

The conditions that the current in the freewheeling loop meets:

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

(8)

where \( I_{coil} \) is the discharge current loaded by the forming coil, \( I_w \) is the induced current in the tube, \( U_0 \) is the initial voltage of the capacitor, and \( M \) is the mutual inductance between the forming coil and the tube.

It is worth that \( M \) is closely related to the coupling coefficient in the electromagnetic flanging system. In electromagnetic flanging, since the tube is in a transient continuous change process, the mutual inductance of the system also follows its transient change, that is, \( M \) is a continuously changing quantity.

Based on the above circuit, this paper introduces a field shaper, which is located between the forming coil and the tube as shown in Fig.6. For this reason, the physical parameters in the electromagnetic flanging system will change. The relevant parameters are consistent except for the discharge voltage, and the detailed parameters are shown in Table 1.
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**Fig. 6.** Equivalent schematic diagram with field shaper

**Table 1** Circuit Parameters

| Parameter                      | Symbol | Value  |
|-------------------------------|--------|--------|
| Capacitance                   | $C$    | 160uF  |
| Line resistance               | $R_{ex}$ | 8mΩ    |
| Line inductance               | $L_{ex}$ | 10uF   |
| Crowbar resistance            | $R_d$  | 10mΩ   |

It can be drew a conclusion that the coupling equivalent inductance has changed after the introduction of the field shaper. The coupling equivalent inductance between the tube and the forming coil in the original electromagnetic flanging system is $M$, which is changed to $M_{c-w} + M_{c-f}$. In addition, the coupling equivalent inductance between the tube and the field shaper is $M_{f-w}$. From the point of view of the circuit, it is not difficult to see that the function of the field shaper is to transfer the induced current generated by the forming coil. After introducing the field shaper into the electromagnetic flanging system, the discharge circuit equation is as follows:

$$
U_c = (R_y + R_e) I_{coil} + L_y \frac{dI_{coil}}{dt} + \left( \frac{dL_y I_{coil}}{dt} + \frac{dM_{c-f} I_f}{dt} + \frac{dM_{c-w} I_w}{dt} \right)
$$

(9)
where $I_{\text{coil}}$ is the discharge current loaded by the forming coil, $I_w$ is the induced current in the tube.

### 3.2 Material

The electromagnetic force at each point of the tube calculated by Eq(1) is used as the load in the structure field to cause the tube to flange, and the deformation at each point of the tube is solved by the following equilibrium equation[12]:

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

(10)

where $\rho$ and $u$ are the density and the displacement vector, $\sigma$ and $F$ are the stress tensor and the electromagnetic force density.

In the calculation of the structural field, the choice of the constitutive equation of material is very important. The constitutive equation mainly describes the relationship between stress and strain during material deformation, and reflects the characteristics of material deformation behavior. For different deformation behaviors, the selection of the constitutive equation directly affects the accuracy of numerical simulation results.

The parameters of the tube (Model: A1060-O) used in this article are the same as those in reference [13]. The thickness and length of the tubes are 1mm and 30mm, and the material parameters are shown in Table 2.
Table 2 The parameters of tube

| Parameters                  | Value                  |
|----------------------------|------------------------|
| The length of tube         | 30mm                   |
| The thickness of tube      | 1mm                    |
| The material of tube       | A1060-O                |
| Density                    | 2.7g/cm³               |
| Electrical conductivity    | 3.77×10⁷S/m            |
| Relative permittivity      | 1                      |
| Relative permeability      | 1                      |
| Young’s modulus            | 6.8×10¹⁰Pa             |
| Poisson’s ratio            | 0.33                   |
| Initial yield tensile strength | 3.2×10⁷Pa              |

With the continuous deepening of materials science research, various constitutive equations that can accurately describe the deformation behavior of materials have been developed. In this article, only electromagnetic flanging at room temperature is considered, and temperature change is not considered. Therefore, the Cowper-Symonds constitutive model which only considers high strain is adopted. The constitutive equation is as follows [14,15]:

\[
\sigma = \sigma_y \left[ 1 + \left( \frac{\dot{\varepsilon}}{C} \right)^m \right]
\]

(11)

where \( \sigma_y \) and \( \varepsilon \) are the yield stress and the plastic strain rate, \( C \) and \( m \) are constant.

4. Results and Discussions

4.1 The Effectiveness

Fig.7 shows the flanging effect of tubes under the same forming coil. The inner diameters of the tubes are 100mm and 110mm respectively in Fig.7(a) and (b). With
the same discharge voltage (3kV), it can be seen that the tube in Fig.7(a). has a significant flanging degree, and the flanging degree of the tube in Fig.7(b). is relatively small. In reality, the flanging angle of the tube (defined as $\theta$) is reduced from $30^\circ$ to $3^\circ$ in Fig.7(a). and (b). Due to the electromagnetic force decays rapidly with the increase of distance, resulting in strict requirements of geometrical matching between the coils and the tubes. Comparing the two models, it can be concluded that $\theta$ decreases rapidly with the increase of the inner diameter of the tube.
After introducing a field shaper into the model, it can be seen clearly that the tube has reached the desired degree of flanging ($\theta_3=90^\circ$) as shown in Fig. 7(c). The length of the inner surface and outer surface of the field shaper is 12.6mm and 4.6mm respectively, and the thickness is 4mm. At this time, the discharge voltage increases to 7.4kV. This means that the field shaper can effectively improve the flanging effect of tubes.

With the same discharge energy (4.38kJ), the current waveform is shown in Fig.8. From the diagram, it can be clearly seen that after the field shaper is added to the entire system, the time at which the discharge current reaches the peak value is advanced by 0.01ms. The main reason is that after introducing the field shaper, $M$ in Eq (5) becomes the superposition of $M_{cw}$ and $M_{cf}$ in Eq(9), and the equivalent inductance of the formed coil increases, resulting in the amplitude and pulse width of discharge current become
smaller.

**Fig.8** Waveforms of discharge currents

Fig.9. shows the distribution of the Lorentz force vector during the electromagnetic flanging process. It can be clearly seen that at different moments, the degree of tube turning is greater relative to the system without field shaper. This is mainly due to the field shaper strengthens the magnetic field in the flanged area of the tube, which makes the electromagnetic force more concentrated.

In this article, the radial displacements of tube under different models are calculated as shown in Fig.10. It can be concluded that under the same discharge energy, the radial displacement of tube in the system with field shaper is larger. The radial maximum values of point A are 8.513mm and 6.167mm respectively. By comparison, the flanging degree of the tube in the system with the field shaper is greater, and the final deformation of the tube is shown in Fig. 11.
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Fig. 9 Distribution of Lorentz force vector at the end of the tube

Fig. 10 Calculated radial displacements at point A
4.2 The energy consumption

In the electromagnetic flanging process, the energy storage capacitor discharges to the tube through the driving coil and makes it flanged under the action of electromagnetic force. The electrical energy of the system is finally converted into deformation energy required for tube flanging. The discharge energy is an important parameter in electromagnetic flanging, which is directly related to process calculation and the quality of the tube. Fig.7(c) and Fig.12 show the flanging effect of tubes with the same inner diameter (110mm). By comparing the two models, it can be concluded that the degree of tube flanging is the same ($\theta_3 = \theta_4 = 90^\circ$). Other conditions are consistent, the discharge voltage of the system with and without the field shaper is 7.4kV and 8.9kV, respectively. The discharge energy of the system can be expressed as:

**Fig.11** 3D simulation deformation diagram: (a) without field shaper; (b) with field shaper
\[ W = \frac{1}{2} CU^2 \]  

Where \( W \) is the discharge energy, \( C \) and \( U \) are the capacitor capacitance and the discharge voltage. According to the above equation, the discharge energy of the system with and without the field shaper can be calculated as 4.38kJ and 6.34kJ, respectively. Obviously, it can be found that adding a field shaper can save 31% of the energy consumption for the entire electromagnetic flanging system.

![Diagram](image)

**Fig.12. Schematic diagram of 110mm tube flanging without field shaper**

### 4.3 The Flexibility

Since the electromagnetic force decays rapidly with the increase of distance, different coils need to be wound when forming different tubes. The inner diameter of the tubes are increased to 120mm as shown in Fig.13. It can be found that in the system without a field shaper, the tube is difficult to achieve the previous effect due to the limitation of distance. Therefore, a larger coil needs to be replaced in the system. With the same discharge energy (5.64kJ), the inner diameter of the forming coil is increased from the
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original 84mm to 95.2mm as shown in Fig.13(a). At this time, the thickness of the field shaper is 9mm. It can be seen that the tube has achieved the ideal flanging effect($\theta_5 = 90^\circ$). Although the tube flanging of different sizes can be realized by changing the coil, it will rise the cost of the whole system and the complexity of the process. The manufacturing process of the forming coil is as follows: First, the corresponding size of the coil bobbin needs to be processed according to the designed scheme, and then the corresponding copper wire is selected for winding on the winding machine. After the coil is wound, it is reinforced with glass fiber and then reinforced with epoxy resin. At the same time, a special "copper nose" must be made, whose function is to connect the incoming and outgoing wires of the coil with the external circuit. It can be seen that the manufacturing process of the forming coil is very complicated. In addition, the raw materials such as reinforcing fiber and epoxy resin used in the winding process are very expensive, and the cost caused by frequent replacement of coils is also very high.

Consequently, a filed shaper can be introduced into the existing electromagnetic flanging device without replacing the coil, as shown in Fig.13(b). Workers only need to cut the copper block into the required shape on the machine tool to complete the processing of the field shaper, which is very simple. In this article, the field shaper is made of the same material as the forming coil. The materials needed to make the field shaper are also cheaper than those for the forming coil. Hence, the method of adding the field shaper brings great flexibility and cost reduction to the existing electromagnetic flanging system.
Fig. 13. Schematic diagram of 120mm tube flanging: (a) without field shaper; (b) with field shaper

5. Conclusions

To overcome the shortcomings of the traditional electromagnetic flanging process, a field shaper is introduced to optimize the process. Our results show that: 1) The flanging angle of the tube (defined as $\theta$) can be increased from $30^\circ$ in model 1 and $3^\circ$ in model 2 to $90^\circ$ in model 3 where a field shaper is introduced into the system.
2) when forming a tube with an inner diameter of 110mm, the discharge voltage can be tuned down from 8.9kV, without the field shaper, to 7.4kV, with the field shaper. That means the energy consumption of the system can be saved by 31%. 3) The manufacturing process of the field shaper is simpler than that of the forming coil, and the cost of the field shaper is lower. In summary, the introduction of a field shaper brings great flexibility to the tube flanging process and improves the economics of the system.
Acknowledgement

I would like to thank Xiang Zhao for his contribution in the writing process and the support by the funding.
Declarations

Funding

This work was supported by the National Natural Science Foundation of China (NSFC) under Project Numbers 51707104, the State Scholarship Fund of China under Project Numbers 201908420196 and Sponsored by Research Fund for Excellent Dissertation of China Three Gorges University under Project Numbers 2020SSPY054.

Availability of data and material

All material data in this article are from previous work, the data is very reliable, and quoted in the article.

Code availability

These simulations are reliable and available and based on the finite element software COMSOL.

Conflicts of interest/Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' contributions

Qi Xiong: Conceptualization, Methodology, Formal analysis, Writing

Zhe Li: Methodology, Software, Investigation, Writing -Original Draft

Jianhua Tang: Formal analysis

Hang Zhou: Software, Visualization
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Meng Yang: Software, Methodology

Xianqi Song: Investigation
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Figure Captions

Fig. 1. Schematic diagram of electromagnetic flanging system: (a) without field shaper; (b) with field shaper

Fig. 2 Structure diagram of solenoid field shaper

Fig. 3 Scheme flow chart

Fig. 4. The geometry of numerical simulation

Fig. 5. Equivalent schematic diagram without field shaper

Fig. 6. Equivalent schematic diagram with field shaper

Fig. 7 Comparison diagram of tube flanging: (a) and (b) without field shaper; (c) with field shaper

Fig. 8 Waveforms of discharge currents

Fig. 9 Distribution of Lorentz force vector at the end of the tube

Fig. 10. Calculated radial displacements at point A

Fig. 11. 3D simulation deformation diagram: (a) without field shaper; (b) with field shaper

Fig. 12. Schematic diagram of 110mm tube flanging without field shaper

Fig. 13. Schematic diagram of 120mm tube flanging: (a) without field shaper; (b) with field shaper