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Study on the Efficiency of Simultaneous Tube Compression and Expansion Electromagnetic Forming

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ABSTRACT The low efficiency of the electromagnetic forming is one of the obstacles for the advancement of this technology. Aiming at solving this issue, this paper presents a double tube-task electromagnetic forming technology method by employing a single driving coil to achieve tube compression and expansion at the same time. On the basis of electromagnetic forming principles and the law of energy conversion, this paper presents a new electromagnetic forming model for double tubes. The magnetic flux density distribution, electromagnetic force distribution and forming efficiency of the tube are analyzed and the effect of the equivalent pulse width of the driving coil current on the forming efficiency is investigated. Results show that in order to maintain the same plastic strain energy of the tube, the initial discharge energy required by the proposed double tube model is 25 kJ which is smaller than that required by a traditional single tube model (33.58kJ) and the efficiency can be improved by about 34.3%. The double tube model attains the maximum forming efficiency near the optimal current pulse width and can improve the low efficiency of traditional electromagnetic forming to a certain extent and provide more possibilities for this technological process.

INDEX TERMS Electromagnetic forming, double-tube, forming efficiency, pulse current.

I. INTRODUCTION

With the day-to-day increase in the utilization of metal tubes of light weigh in various industry applications such as oil and gas, water pipes, drainage, ships, and aerospace, the requirement of high surface quality has been increased [1]–[6]. Compared with the traditional processing method, electromagnetic forming is a high-speed forming technology that features several advantages including high strain rate, non-contact and single mold processing that makes it an ideal technology for tube processing [7]–[12].

The energy used in the electromagnetic forming process is initially stored as an electrical energy in a capacitor bank, which is converted into electromagnetic force to shape the workpiece. It was found that only 20% or less of the stored electric energy in the capacitor is transformed into the forming energy of the workpiece [13]. In [14], experimental testing using driving coils made of spring steel, shows that the efficiency of the electromagnetic forming process is only 2%. This low efficiency is attributed to the significant Joule loss in the coil and the field shaper. Detailed analysis to the mechanical energy impact on the forming process is presented in [15] in which the law of kinetic energy, forming energy and accumulated mechanical energy over time are explained. During the forming process, the equivalent pulse width of the discharge current is a key parameter in identifying the overall forming efficiency [10], [16]. Reported results in [17] concluded that the optimal frequency to achieve maximum deformation is also one of the key parameters for the optimal design of electromagnetic forming systems. The influence of capacitance on the equivalent pulse width and hence forming efficiency during tube electromagnetic expansion is presented in [18]. Reported results in this paper show that under certain discharge energy, there is an optimal capacitance

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value that can maximize the expansion of the tube. On this basis, the forming process of tube compression is presented in [19] that reported a maximum forming efficiency of 13.76% at an optimum equivalent current pulse width. While this is a considerable high efficiency, it is obtained for tube compression only.

This paper presents a new double tube electromagnetic forming technology using a single driving coil to process two tubes at the same time. In this regard, an electromagnetic-structure coupling model is established. The electromagnetic force distribution of the proposed double-tube electromagnetic forming model, traditional single-tube compression model and traditional single-tube expansion model are numerically analyzed and compared under different conditions.

TABLE 1. Basic parameters of the model.

Symbol	Description	Value
C	capacitance	320 μF
L_L	Line inductance	6.5 μH
R_L	Line resistance	0.025 Ω
R_d	Freewheeling resistance	0.2 Ω
ρ	density	2700 kg/m^3
σ_w	Conductivity	3.72e^7 S/m
σ_s	Initial yield stress	95 MPa
V_s	Poisson's ratio	0.33
E_w	Young's modulus	68 GPa

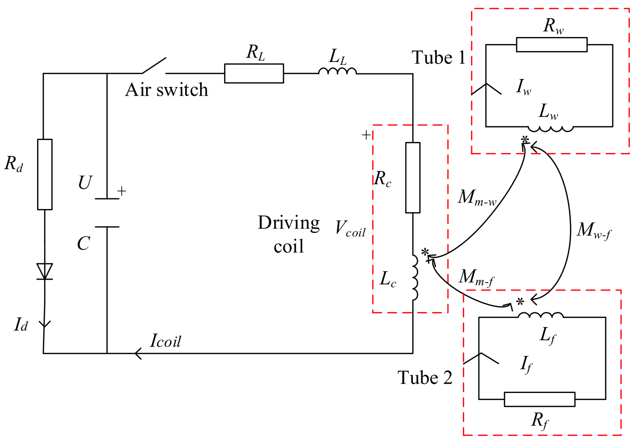

FIGURE 1. Equivalent circuit of the proposed double-tube forming system.

II. ELETROMAGNETIC FORMING PRINCIPLE

In the double tube electromagnetic forming model, tubes are placed on both sides of the driving coil as shown in the equivalent circuit of Figure 1 whose parameters are listed in Table 1. A pulse current is generated by discharging the capacitor stored energy into the driving coil which induces an eddy current in the two tubes. The pulse and induced eddy currents interact and produces a huge electromagnetic force pulse, which drives the two tubes to accelerate and deform. The equivalent circuit is a typical RLC circuit, which contains energy storage capacitor, connection lines, driving coil, two tubes and freewheeling circuits. The freewheeling circuit is aimed at reducing the accumulation of heat in the system to increase the life of the capacitor and the driving coil.

The current and voltage balance equations of the circuit shown in Figure 1 can be written as:

$$-C\frac{d}{dt}U + I_{\text{coil}} + \frac{U}{R_d} = 0 \tag{1}$$

where $C\frac{d}{dt}U$ is the capacitance current, I_{coil} is the pulse current of the driving coil, $\frac{U}{R_d}$ is the freewheeling loop current.

$$V_{coil} = R_C I_{coil} + L_C\frac{d}{dt}I_{coil} + M_{m-w}\frac{d}{dt}I_w + M_{m-f}\frac{d}{dt}I_f \tag{2}$$

$$U - R_L I_{\text{coil}} - L_L\frac{d}{dt}I_{\text{coil}} - V_{coil} = 0 \tag{3}$$

where U is the capacitor voltage, $(R_L + R_C)\,I_{\text{coil}}$ is the line and coil resistances' voltage drop, $L_L\frac{d}{dt}I_{\text{coil}}$ is the line inductance voltage drop, $L_C\frac{d}{dt}I_{\text{coil}}$ is the coil self-inductance voltage drop, M_{m-w}, M_{m-f} are the mutual inductances between the driving coil and tube-1 and tube-2 coils; respectively, and I_w and I_f are the respective induced currents in the two tubes.

The following electro-magnetic coupling equations are important to describe the electromagnetic forming process [20].

$$R_w I_w + L_w\frac{dI_w}{dt} + M_{w-m}\frac{dI_c}{dt} + M_{w-f}\frac{dI_f}{dt} = 0 \tag{4}$$

$$R_f I_f + L_f\frac{dI_f}{dt} + M_{f-m}\frac{dI_c}{dt} + M_{f-w}\frac{dI_w}{dt} = 0 \tag{5}$$

$$M_{m-w} = M_{w-m} \tag{6}$$

$$M_{m-f} = M_{f-m} \tag{7}$$

$$M_{w-f} = M_{f-w} \tag{8}$$

where M_{w-m}, M_{f-m} are the mutual inductances between primary and secondary circuits of tube-1 and tube-2; respectively, and M_{w-f}, M_{f-w} are respectively the mutual inductances between the secondary circuits of tube-1 and the tube-2. These mutual inductances couple the electric and magnetic fields.

Finally, the equivalent circuit needs to satisfy the below freewheeling loop current balance equation.

$$I_d + (U < 0)\frac{U}{R_d} = 0 \tag{9}$$

For the traditional single tube electromagnetic forming system, the voltage drop $M_{m-f}\frac{d}{dt}I_f$ induced on one of the tubes is to be eliminated. It is also to be noted that in the double-tube electromagnetic forming model, the equivalent inductance of the entire discharging circuit will be reduced, so the pulse width of the discharge current is also reduced.

The energy used in the electromagnetic forming process is initially stored in the capacitor bank. After the electromagnetic forming process is completed, this energy is converted into plastic strain energy to change the shape of the tube. Between these two stages, a complex energy transfer process takes place. Due to the losses in the discharge circuit and energy loss in the switch, only a part of the stored energy in the capacitor is transferred to the coil.

Moreover, the energy loss caused by the temperature rise of the coil and the leakage magnetic flux reduces the magnetic coupling strength with the tubes. The temperature rise caused by the eddy currents in the tubes and the unused magnetic field energy results in less conversion energy into the tube plastic strain energy. The initial capacitor electric energy E_0 and the plastic strain energy E_p of the tube are calculated as below:

$$E_0 = \frac{1}{2}CU^2 \tag{10}$$

$$E_p = \frac{1}{2}\sigma\varepsilon V \tag{11}$$

where σ and ε are the stress and strain; respectively.

Then the forming efficiency is calculated from:

$$\eta = \frac{E_p}{E_0} \tag{12}$$

As per the literature, the efficiency of the tube electromagnetic forming is usually less than 20% [10].

III. ELECTROMAGNETIC FORMING SIMULATION MODEL

The electromagnetic forming process involves multi-coupling of electromagnetic and structural fields. COMSOL commercial finite element software is used to establish the electromagnetic-structure coupling two-dimensional axisymmetric model for the proposed double-tube, traditional single-tube compression and traditional single-tube expansion processes based on the flowchart of Figure 2 which includes four modules:

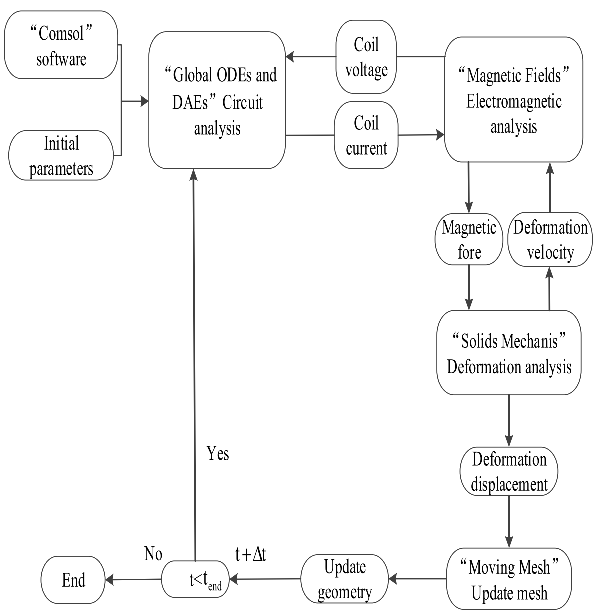

FIGURE 2. Flow chart of tube electromagnetic forming model.

(1) *Global Ordinary Differential and Differential Algebraic Equations module* which is used to simulate the discharge process and calculate the driving coil current based on equations (1) to (9). The module uses these equations to realize the freewheeling circuit, thereby increasing the life of the capacitor and the driving coil. The module uses I_{coil} and V_{coil} to realize field-circuit coupling.

(2) *Magnetic Field module* is mainly used to calculate the magnetic flux density, eddy current and electromagnetic force distribution in the spatial domain. At the same time, it provides electromagnetic force load to the "Solid Mechanics" module. After the pulse current flows into the driving coil, the induced magnetic field variation is analyzed, and the instantaneous magnetic field and electromagnetic force are calculated. By ignoring the influence of the axially progressive spiral of the solenoid coil, the coil can be considered as the equivalence of multiple closed rings. Hence, the structure and load of the driving coil are axisymmetric, which can be simplified to a two-dimensional axisymmetric model. In this model, the electric field intensity E and the current density J only have components in the φ direction, while the magnetic flux density B can be decomposed into components in the r and z directions. The two-dimensional axisymmetric form of Maxwell's equation is:

$$\nabla \times \mathbf{E}_{\boldsymbol{\varphi}} = -\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \times (v \times \boldsymbol{B}) \tag{13}$$

$$\boldsymbol{J}_{\boldsymbol{\varphi}} = \gamma \boldsymbol{E}_{\boldsymbol{\varphi}} \tag{14}$$

$$\nabla \times \boldsymbol{H} = 0 \tag{15}$$

where v is the tube velocity and γ is the tube conductivity.

The two terms on the right side of (13) represent the curl source of the induced electric field intensity caused by the change of the magnetic flux and the movement of the tube. In the process of tube compression or expansion, the electromagnetic force load, given by (16) and (17), is mainly a radial electromagnetic force F_r which is proportional to J_φ and B_z while the axial electromagnetic force component F_z is dominated by the radial magnetic field density B_r which is not significant. Therefore, in the electromagnetic forming process, B_z plays a major role in the forming effect of the workpiece, so it is essential to analyze the temporal and spatial distribution of B_z.

$$\boldsymbol{F_r} = \boldsymbol{J_\varphi} \times \boldsymbol{B_z} \tag{16}$$

$$\boldsymbol{F_z} = \boldsymbol{J_\varphi} \times \boldsymbol{B_r} \tag{17}$$

(3) *Solid Mechanics module* is used to simulate the acceleration of the tube and the plastic deformation. The electromagnetic-structure coupling is realized by feeding the deformation to the "magnetic field" module. The tube displacement equation is:

$$\nabla \cdot \boldsymbol{\sigma} + \boldsymbol{F} = \rho \frac{\partial^2 \mathbf{u}}{\partial t^2} \tag{18}$$

where σ is the stress tensor, ρ is the tube density, and u is the displacement vector.

Since the process is classified as a high strain rate forming, the effect of high strain rate on the material needs to be considered. In this paper, the Cowper-Symonds model is used to simulate the tube plastic deformation behavior as per the below constitutive equation.

$$\sigma = \left[1 + \left(\frac{\varepsilon_{pe}}{C_m}\right)^m\right]\sigma_{ys} \tag{19}$$

where σ is the flow stress of the tube during high-speed deformation, m is the strain rate hardening parameter, C_m is the viscosity, and σ_{ys} is the flow stress under quasi-static condition. In the simulation model, $C_m = 6500$ and $m = 0.25$ [21].

This treatment could be acceptable for welding analysis which has been extensively adopted in the literature [22], [23].

In this model, six sets of second Piola-Kirchhodd stress and strain rate tensors are employed. Then the equation is used to integrate the volume of the tube along the tube wall and height after which the plastic strain energy is calculated.

(4) *Mobile mesh module* is used to update the air domain grid near the tubes to increase the calculation accuracy.

IV. RESULTS AND DISCUSSION

In the electromagnetic forming process, the first pulse of the electromagnetic force applied to the tube contributes to its deformation and movement including kinetic energy and plastic strain energy [24], [25]. Figure 3 shows the current waveforms of four groups of driving coils with different forming models. As the equivalent inductance of the double-tube model is less than that of the single-tube model and the single-tube model inductance is less than the no-tube model, then the peak current of the driving coil in the double-tube model is greater than that in the single-tube model which in turns is greater than that of the no-tube model and the current pulse width is slightly reduced. It can be also observed that the current waveforms of the driving coil for single tube expansion and single tube compression are basically the same.

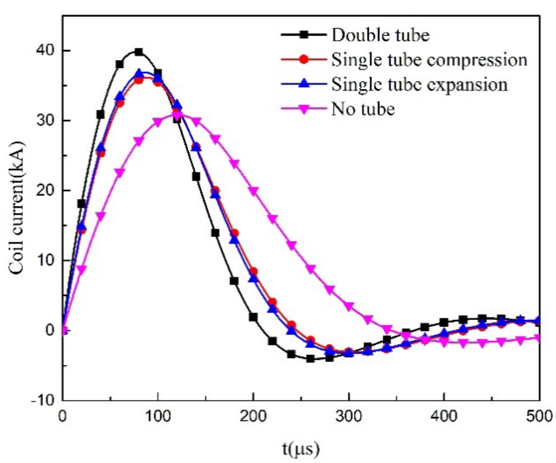

FIGURE 3. Current waveforms of four driving coils with different forming models.

It can be seen from (16) and (17) that the electromagnetic force on the tubes is directly proportional with the magnetic flux density. As the axial magnetic flux density dominates the generated electromagnetic force, its profile at the gaps between the tubes and the driving coil, denoted by points **a** and **b** in the simulation model shown in Figure 4, is investigated for four models; traditional single tube expansion, traditional single tube compression, no loaded tube i.e. when the driving coil is just discharging its energy and the proposed double tube. Results are shown in Figure 5.

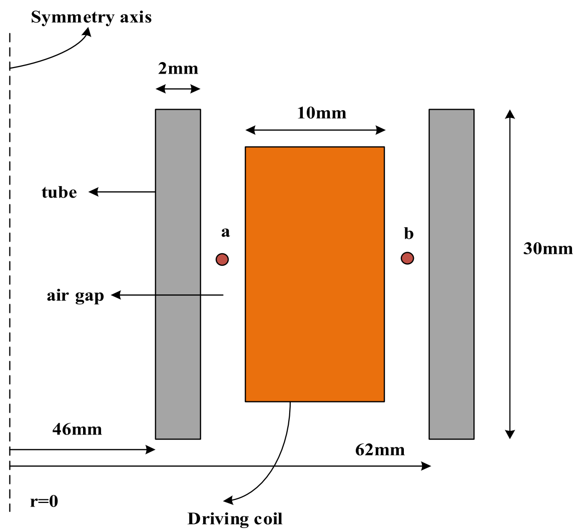

FIGURE 4. Double tube electromagnetic forming simulation model.

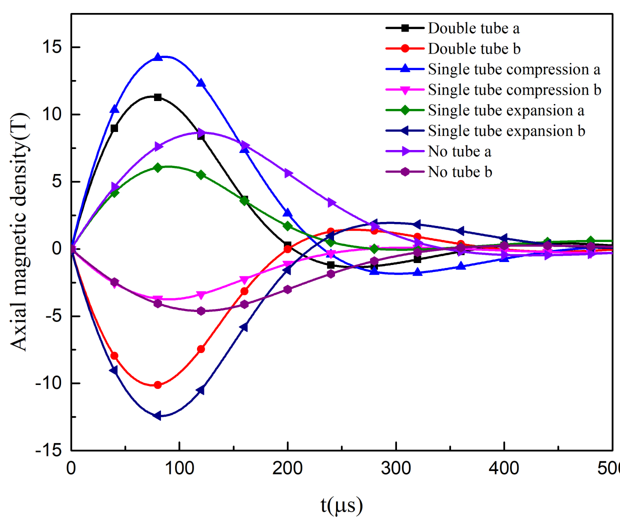

FIGURE 5. Axial magnetic flux density of the investigated models at points a and b pf Figure 4.

For point **a**, results show that the peak value of the axial magnetic flux density of the traditional single tube compression reaches 14.29T which is larger than the corresponding peak value of the double-tube model that has a crest value of 11.30T. This is also larger than the magnetic flux density when no tube is loaded and larger than the magnetic flux density when the traditional single tube is expanded. Similarly, for point **b**, the largest peak axial magnetic flux density of 12.36T is attained for the traditional single tube expansion followed by a peak value of 10.14T that is achieved by the double-tube model. This is also greater than the magnetic flux density when the tube is not loaded and when the traditional single tube is compressed.

The current in the driving coil is the source of the magnetic flux density, so the pulse width of the current in the double-tube model is also slightly smaller than the two traditional single-tube models that exhibit almost the same current pulse width as previously shown in Figure 3. Results in Figure 5 reveal that when the tube is not loaded, the magnetic flux density at points **a** is greater than the magnetic flux density at the same point when the traditional single tube is expanded. On the other hand, the magnetic flux density at point **b** for unloaded tube is greater than the magnetic flux density at the same point when the traditional single tube is compressed. Compared with the unloaded tube model, the magnetic field at the two points **a** and **b** is a composite magnetic field that is generated by the driving coil and the tube eddy current. The composite magnetic field outside the tube and the driving coil is weakened. The skin effect of the tube is an important electrical parameter to be considered during the forming process as it affects the electromagnetic field distribution near the tube. The skin depth δ in the tube depends on the discharge frequency f, the electrical conductivity σ, and the magnetic permeability of the tube μ as per the below equation.

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad (20)$$

Using (20), the skin depth of the used tubes of 2mm thickness is found to be about 2mm. Therefore, the skin effect has no considerable influence on the electromagnetic distribution on the tubes and can be ignored. The reason for the decrease in the peak value of the axial magnetic flux density in case of double-tube model is that when the driving coil processes two tubes at the same time, the coupling effect between the eddy current in the two tubes generates corresponding magnetic fields that are in opposite direction. Hence, the synthetic magnetic field in which the tubes are located is further weakened, which inhibits the tubes forming effect.

As shown in Figure 6, the generated electromagnetic force by the traditional single-tube compression or expansion is much greater than the electromagnetic force on the corresponding tube due to the double-tube model. At the same time, the electromagnetic force received by the traditional single tube during compression is slightly greater than that received by the traditional tube during expansion process. This is attributed to the larger axial magnetic flux density when the tube is compressed than that when the tube is expanded. In the double-tube model, the electromagnetic force received by the tube during simultaneous compression and expansion forming is almost the same. The energy efficiency of the manufacturing process to obtain maximum plastic strain energy is necessary to be calculated to assess the effectiveness of the entire process. Considering the double-tube model processes two tubes at the same time, hence the overall efficiency of the system is better than that of the single tube electromagnetic forming.

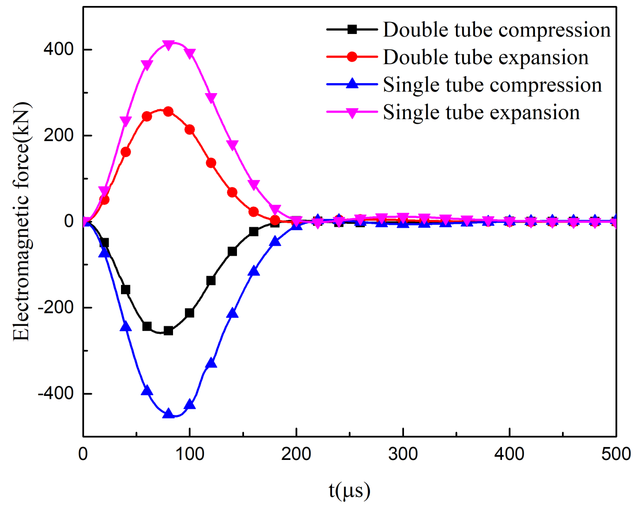

FIGURE 6. Electromagnetic force distribution of the investigated models.

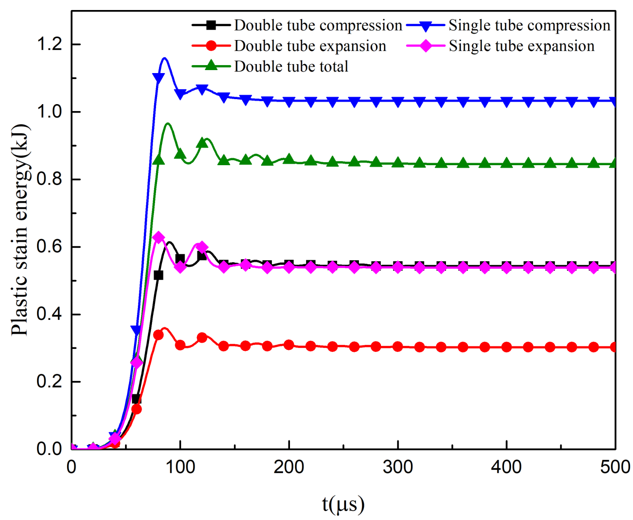

FIGURE 7. Plastic strain energy of the three models.

The plastic strain energy of the tube for the investigated models is shown in Figure 7. When the electromagnetic force acts on the tube, the tube plastic strain energy increases. Whenever there is a stress on a sheet element, there will be also some elastic strain. While this elastic strain is small, it may have a significant impact on the process due to the considerable elastic recovery during unloading, which results in springback effect. This explains why the plastic strain energy of the tube reaches a peak value at 80μs and then reaches a valley at 115μs after which it starts to stabilize. It can be seen from Fig. 7 that the plastic strain energy is 1.033kJ, 0.539kJ and 0.859kJ for the traditional tube compression, traditional tube expansion and the double-tube model; respectively. With an initial electric energy E_0 in the capacitor of 16kJ, the forming efficiency is 6.46% for single tube compression, 3.37% for single tube expansion and 5.37% for the double-tube model. Compared with the traditional single tube expansion, the forming efficiency is increased by 59.35% for the double-tube model that exhibits a 16.87% less forming efficiency when compared with the traditional single tube compression. Because plastic strain energy is integrated by multiplying the stress by the strain, before the yield stage, the tube stress-strain curves are almost identical for the expansion and compression processes. After reaching the yield stage, the stress and strain of the tube during compression become inversely proportional while it remains stable in case of tube expansion. This causes the plastic strain energy of the tube compression to be much larger than that of the tube expansion under the same conditions. Since the electromagnetic force on the tube in the double-tube model is half of the electromagnetic force on the tube in the single tube model, the plastic strain energy of each tube in the double-tube model is much smaller than that of the traditional single tube forming and is close to half.

In order to better describe the improvement of the electromagnetic forming efficiency by the double tube model, the initial discharge energy under the same parameters is changed and the plastic strain energy of each tube in the double-tube model is obtained. Then for the same plastic strain energy in the double-tube model, the required initial discharge energy by the traditional single tube model is calculated as listed in Table 2. It can be seen that the double-tube model can effectively process two tubes at the same time, which facilitates the full utilization of the discharge energy.

TABLE 2. Discharge energy of the same plastic strain energy.

Double tube(kJ)	Single tube compression (kJ)	Single tube expansion(kJ)	Increase rate(%)
9	5.607	6.350	32.86
12.25	7.84	8.18	30.78
16	9.734	11.022	29.725
20.25	12.674	13.542	29.46
25	15.936	17.640	34.304
30.25	18.49	20.503	28.90
36	21.53	24.01	26.5

The discharge frequency is another key parameter in the forming process, and the rationality of its selection is directly related to the forming energy conversion efficiency. The optimum frequency is that corresponding to the largest deformation and the greatest plastic strain energy of the tube [20]. The discharge frequency of the electromagnetic forming system depends on the inductance, resistance and capacitance values of the equivalent RLC circuit. For a given group of driving coils and tubes, the discharge frequency is controlled by changing the capacitance value. Under the assumption the initial electric energy E_0 (16kJ) in the capacitor is constant, the discharge voltage should also change while changing the capacitance as shown in Table 3.

The electromagnetic force distribution of the double-tube model under different discharge current pulse widths is shown in Figure 8. Results show that the electromagnetic force distribution along each tube is basically the same, and the peak value of the electromagnetic force decreases with the increase of the discharge current pulse width. When the capacitance is 10μF, the electromagnetic force is the largest while the current pulse width is the smallest, and the time for the electromagnetic force to act on the tube is the shortest. On the other hand, when the capacitance is 640μF, the electromagnetic force attains the smallest level, the current pulse width is the largest, and the electromagnetic force acts on the

TABLE 3. Capacitance and discharge voltage.

Capacitance(μF)	Discharge(kV)
10	56.57
20	40
30	32.66
40	28.28
60	23.09
80	20
120	16.33
160	14.14
240	11.545
320	10
480	8.16
640	7.07

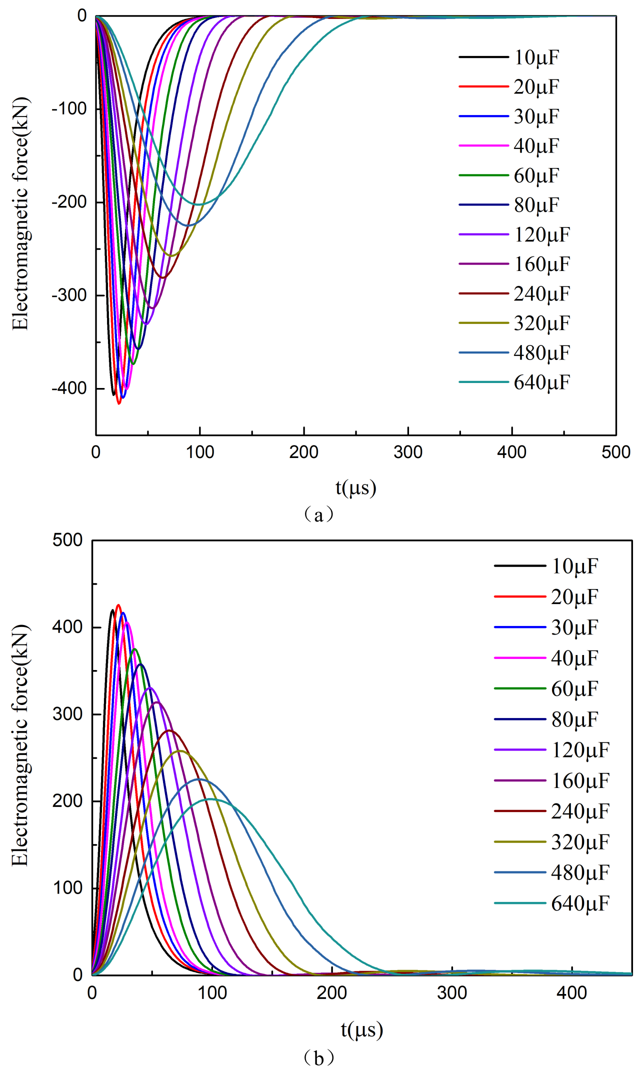

FIGURE 8. Electromagnetic force of double-tube model with different current pulse widths: (a) compression, (b) expansion.

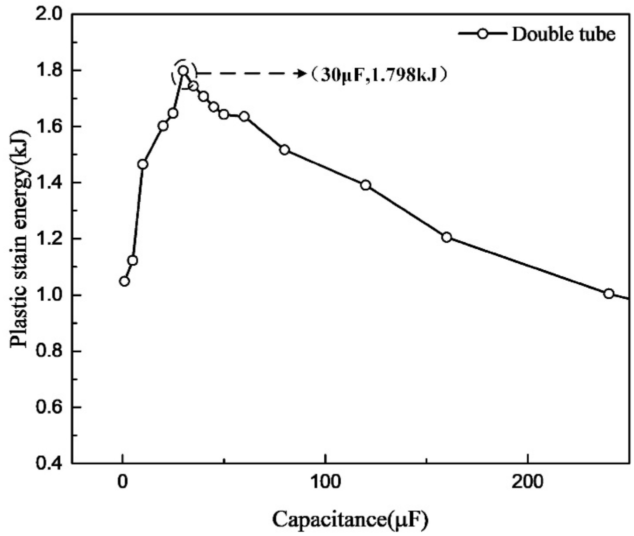

FIGURE 9. Tube plastic strain energy with different capacitance values.

tube for a longer time. Therefore, there is an optimal current pulse width that can optimize the forming efficiency.

The initial discharge energy is much greater than the plastic strain energy, because in addition to the kinetic energy and plastic strain energy, it also includes the leakage of the tube and internal energy heat loss. In the forming process, kinetic energy is further transformed into plastic strain energy, and the ratio of the final plastic strain energy to the initial discharge energy is the efficiency of electromagnetic forming. In order to obtain the best current pulse width to optimize the forming efficiency, the relationship between the capacitance value and the plastic strain energy of the tube when the electric energy in the capacitor is kept constant is plotted as shown in Figure 9. The obtained results suggest that the plastic strain energy of the double-tube model will first increase and then decrease with the increase of the capacitance and there is an optimal capacitance value to achieve maximum plastic strain energy [20]. Under the suggested optimal capacitance value (30μF), the plastic strain energy of the double-tube model is 1.798kJ, and the corresponding efficiency is 11.24%.

V. CONCLUSION

This paper proposes an electromagnetic forming technology for simultaneous processing of double tubes. The proposed system can improve the low efficiency of traditional single-task electromagnetic forming to a certain extent and provide more opportunities for the promotion of this technology. Four sets of comparison models including the proposed double-tube forming system, traditional single tube compression, no-tube model and traditional single tube expansion are proposed. Numerical and simulation results show that the electromagnetic forming of the double tubes can provide electromagnetic force for two tubes at the same time, and the forming effects of compression and expansion can be generated separately. Furthermore, the forming efficiency can be increased by 34.3% compared with the traditional single tube forming. Results also show that when the discharge energy is constant (16kJ), there is a suitable driving coil current pulse width to maximize the forming efficiency (11.24%) of the double-tube electromagnetic forming. The electromagnetic forming of the double tubes can solve the problem of low efficiency of electromagnetic forming to a certain extent. Experimental validation is to be carried out in future research studies.

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