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Research on Forming Efficiency in Double-Sheet Electromagnetic Forming Process

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ABSTRACT Improving the forming efficiency at a reasonable cost has been the main challenge in the electromagnetic forming technology. Towards this aim, this paper proposes a simultaneous cost-effective double-sheet electromagnetic forming method using single driving coil. In order to highlight the features of the proposed technique, comparison of the performance of five electromagnetic forming models is presented. These models include a no-sheet model, single-sheet stationary model, single-sheet moving model, double-sheet stationary model and double-sheet moving model. For each model, electromagnetic force distribution and forming efficiency of the workpiece are analyzed. Furthermore, the influence of the pulse current width of the driving coil on the electromagnetic forming efficiency of the plate is investigated for all models. Results show that for the same system discharge parameters, electromagnetic forming efficiency of double-sheet is 21.14% whereas the single-sheet electromagnetic forming model only achieves 14.68% efficiency. Thus, the double-sheet electromagnetic forming technology can improve the low forming efficiency of a single-sheet electromagnetic forming method and at the same time, the method can form two workpieces simultaneously which makes it more cost effective than the single-sheet method.

INDEX TERMS Electromagnetic force, electromagnetic forming technology, double-sheet model, forming efficiency.

I. INTRODUCTION

Electromagnetic forming (EMF) is an industrial technology that uses high speed pulsed electromagnetic force to achieve a forming process for metal material [1]–[3]. The electromagnetic forming technology features high strain rate ($10^3 - 10^5 s^{-1}$) and hence [4]–[7], it can improve the material plastic deformation ability and increase the forming limit by 5 to 10 times when compared to traditional machining processing [8]–[9]. Moreover, as the process does not involve any workpiece contact force, EMF technology features reduced stress on the workpiece and high surface quality of the resulted product [10]–[12].

The main challenge of the EMF technology is the improvement of the forming efficiency using cost effective techniques. This has motivated researchers to investigate several techniques in order to improve the EMF efficiency. For instance, Psyk V and Risch D pointed investigated the EMF efficiency through investigating the ratio of the mechanical energy exerted on the workpiece to the total energy of the system [13]. Zhang et al. investigated the influence of effect of the driving coil pulse current width on the efficiency of a tube electromagnetic bulging process [14]. Yu et al. simulated the dynamic process of a tube electromagnetic compression and a maximum forming efficiency of 13.76% was reported [15]. A high intensity driving coil was presented in [16] to optimize the width of the pulse discharge current and hence improving the forming efficiency of a sheet electromagnetic bulging process. Cao Quanliang et al. investigated the impact of sheet thickness and current frequency on the forming efficiency [17]. Reported results a strong correlation of the above two parameters and the workpiece forming efficiency [17].

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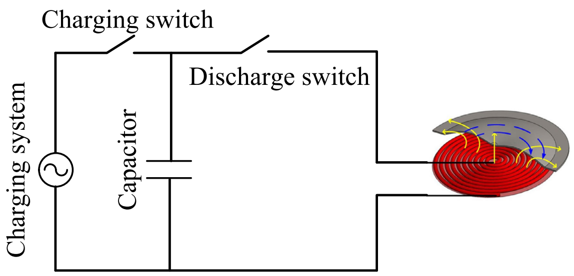

FIGURE 1. Schematic diagram of the EMF process.

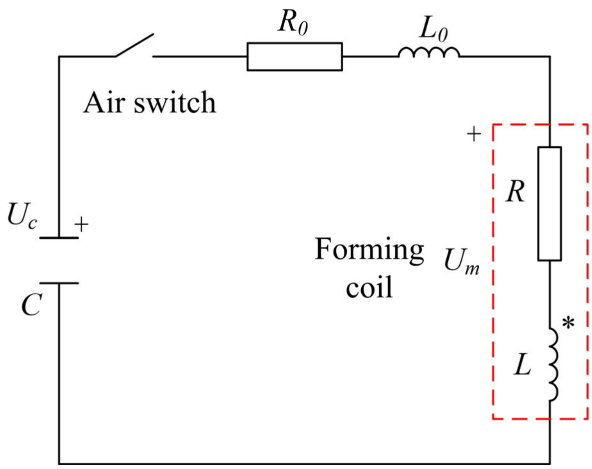

FIGURE 2. Equivalent circuit of the no-sheet EMF dischar ge model.

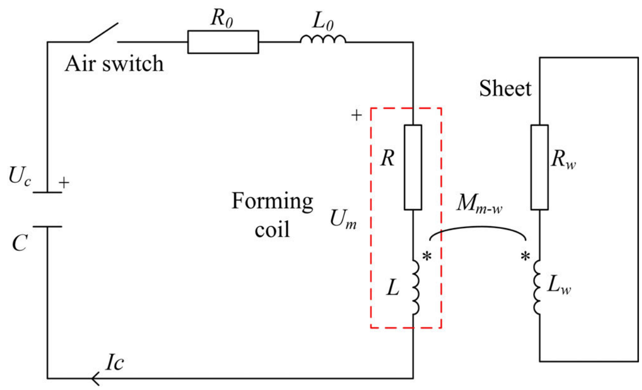

FIGURE 3. Equivalent circuit of the single-sheet EMF discharge model.

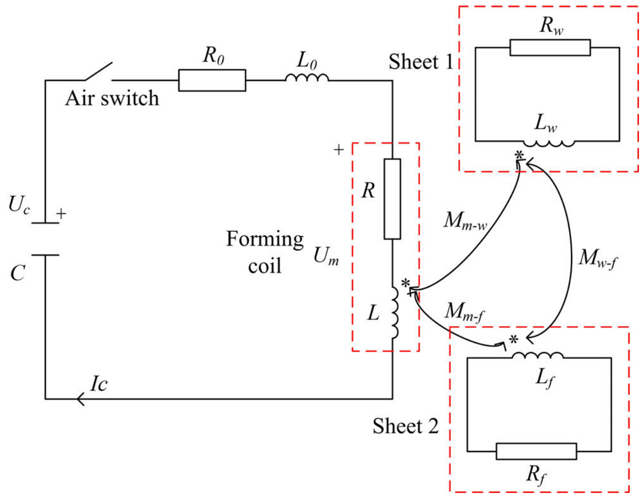

FIGURE 4. Equivalent circuit of the double-sheet EMF discharge model.

In order to further improve the efficiency of metal sheet EMF while maintaining the cost of the hardware setup, this paper presents a new EMF approach that utilizes a single driving coil to form two sheets at the same time. This double-sheet EMF technology is investigated through building an electromagnetic-structure coupling model for the traditional sheet electromagnetic forming process that is validated experimentally. The advantage of the proposed model is highlighted through detailed comparison with no-sheet, single-sheet, and double-sheet the forming models.

II. BASIC PRINCIPLE

A schematic diagram of the basic principle of the EMF process is shown in Figure 1. The capacitor power supply is used to discharge stored electrostatic energy to the driving coil to generate a pulse current which induces eddy current in the metal workpiece [18]–[20]. The coil pulsed current interacts with the workpiece induced eddy current to generate a pulsed electromagnetic force. This force accelerates the workpiece at high speed and deform instantly to complete the forming process [19], [21], [22].

When there is no sheet, the equivalent circuit of the EMF model is as shown in Figure 2 which can be modelled using Kirchhoff's laws as below:

$$\begin{cases} (R_0+R)\boldsymbol{I_c}+(L_c+L)\dfrac{d\boldsymbol{I_c}}{dt}=\boldsymbol{U_c} \\ \boldsymbol{U_c}=\boldsymbol{U_0}-\dfrac{1}{C}\int_0^t \boldsymbol{I_c}dt \end{cases} \tag{1}$$

When there is one sheet on one side of the driving coil, the equivalent circuit is modified to the one shown in Figure 3 with the following circuit equation:

$$\begin{cases} (R_0+R)\boldsymbol{I_c}+(L_c+L)\dfrac{d\boldsymbol{I_c}}{dt}+M_{m-w}\dfrac{d\boldsymbol{I_w}}{dt}=\boldsymbol{U_c} \\ R_{\mathrm{w}}\boldsymbol{I_w}+L_w\dfrac{d\boldsymbol{I_w}}{dt}=0 \\ \boldsymbol{U_c}=\boldsymbol{U_0}-\dfrac{1}{C}\int_0^t \boldsymbol{I_c}dt \end{cases} \tag{2}$$

This paper proposes two metal sheets placed on both sides of the driving coil. The equivalent circuit of this model is shown in Figure 4 and the circuit equation can be expressed as:

$$\begin{cases} (R_0+R)\boldsymbol{I_c}+(L_c+L)\dfrac{d\boldsymbol{I_c}}{dt}+M_{m-w}\dfrac{d\boldsymbol{I_w}}{dt}+M_{m-f}\dfrac{d\boldsymbol{I_f}}{dt}=\boldsymbol{U_c} \\ R_{\mathrm{w}}\boldsymbol{I_w}+L_w\dfrac{d\boldsymbol{I_w}}{dt}=0 \\ R_{\mathrm{f}}\boldsymbol{I_f}+L_f\dfrac{d\boldsymbol{I_f}}{dt}=0 \\ \boldsymbol{U_c}=\boldsymbol{U_0}-\dfrac{1}{C}\int_0^t \boldsymbol{I_c}dt \end{cases} \tag{3}$$

In the above equations, where ***Uc*** is the capacitor voltage, ***Ic*** is the driving coil current; ***Iw*** and ***If*** are the induced

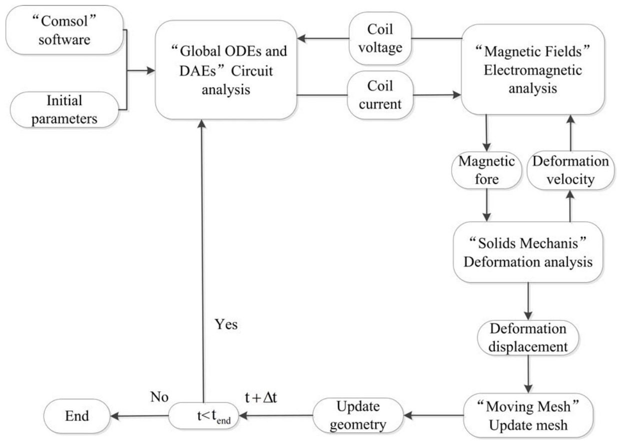

FIGURE 5. Flow chart of the EMF simulation using COMSOL software.

currents in the two sheets and *Mm-w* and *Mm-f* are the mutual inductances between the two sheets and the driving coil.

It is to be noted that the existence of the metal sheet decreases the circuit overall inductance due to the existence of mutual inductance and hence the width of the pulse current will be reduced accordingly.

III. ELECTROMAGNETIC-STRUCTURE COUPLING MODEL

The EMF process is modelled using a complex nonlinear model involving mutual coupling of electromagnetic and structural fields. Finite element analysis can be used to emulate this physical process [23]. In this paper, two-dimensional axisymmetric model of the electromagnetic structure coupling for EMF of sheet bulging is established using COMSOL software as shown in the flowchart of Figure 5 that comprises 4 modules as briefly described below.

-*Global Ordinary Differential and Differential Algebraic Equations module*: simulates the discharge circuit and calculates the driving coil current based on Eqns. (1)-(3).

-*Magnetic field module*, calculates the magnetic field, eddy current and electromagnetic force distributions.

-*Solid Mechanics module*, simulates the deformation process of sheet parts driven by electromagnetic force.

-*Moving Grid module*, updates the air grid around the sheet.

In the process of sheet EMF, the structure of the driving coil, workpiece and the source of the electromagnetic field is of spatial symmetry, which can simplify the entire system into a two-dimensional axisymmetric model. In this model, the induced eddy current in the sheet is mainly dominated by the hoop component as described by the below equations.

$$\nabla \times \boldsymbol{E}_{\varphi} = -\frac{\partial \boldsymbol{B}_z}{\partial t} + \nabla \times (\boldsymbol{v}_z \times \boldsymbol{B}_r) \tag{4}$$

$$\boldsymbol{J}_{\varphi} = \gamma \boldsymbol{E}_{\varphi} \tag{5}$$

where $\boldsymbol{E}$ is the electric field intensity,$\boldsymbol{B}$ is the magnetic flux density, $\boldsymbol{v}$ is the workpiece speed; $\boldsymbol{J}$ is the current density, γ is the workpiece conductivity. Subscripts $\boldsymbol{r}$, φ and $\boldsymbol{z}$ represent the radial, hoop and axial components of the vector; respectively.

TABLE 1. System parameters used in the numerical simulation model [24].

Symbol	Description	Value
C_0	Capacitance	320μF
U_0	Discharge voltage	8kV
S	Copper wire cross section	1mm×4mm
R_0	Line resistance	25mΩ
L_0	Line inductance	6.5μH
H_c	Coil height	17.5mm
D_{in}	Coil inner diameter	23mm
D_{out}	Coil outer diameter	70mm

The electromagnetic force $\boldsymbol{F}$ exerted on the sheet is determined by the induced eddy current and the magnetic flux density as below:

$$\boldsymbol{F}_z = \boldsymbol{J}_{\varphi} \times \boldsymbol{B}_r \tag{6}$$

$$\boldsymbol{F}_r = \boldsymbol{J}_{\varphi} \times \boldsymbol{B}_z \tag{7}$$

The sheet is mainly deformed in the axial direction and the axial electromagnetic force density is mainly determined by the circumferential induction eddy current and the radial magnetic flux density.

When the sheet is subjected to electromagnetic force, sheet displacement satisfies Newton's law i.e.:

$$\nabla \cdot \sigma + \boldsymbol{F} = \rho \frac{\partial^2 \boldsymbol{u}}{\partial t^2} \tag{8}$$

where ρ is the sheet density; $\boldsymbol{u}$ is the displacement vector; $\boldsymbol{F}$ is the electromagnetic force density.

The EMF is a high strain rate process that influence the material of the workpiece. In the analysis presented in this paper, AA5083-O plate is simulated using Cowper-Symonds model based on the below equation:

$$\sigma = [1 + (\frac{\varepsilon_{pe}}{P})^m]\sigma_{ys} \tag{9}$$

where σ is the flow stress of the sheet under high-speed deformation, m is the strain rate hardening parameter, P is the viscous parameter, and σ_{ys} is the flow stress under quasi-static condition. For aluminum alloy material, P and m are $6500s^{-1}$ and 0.25, respectively.

IV. SIMULATION AND EXPERIMENTAL RESULTS

In order to validate the simulation model used in this paper, model simulation results are compared with the experimental results published in [24].

In experimental hardware setup in [24], the sheet material is AA5083-O aluminum alloy of 90mm radius and 2mm thickness. Other system parameters are listed in Table 1. These parameters are used to simulate the single-sheet EMF model shown in Figure 6(a) and the double-sheet EMF model shown in Figure 6(b).

Figure 7 shows the driving coil current waveforms obtained using simulation model in this paper and experimental results published in [24] without considering the crowbar circuit.

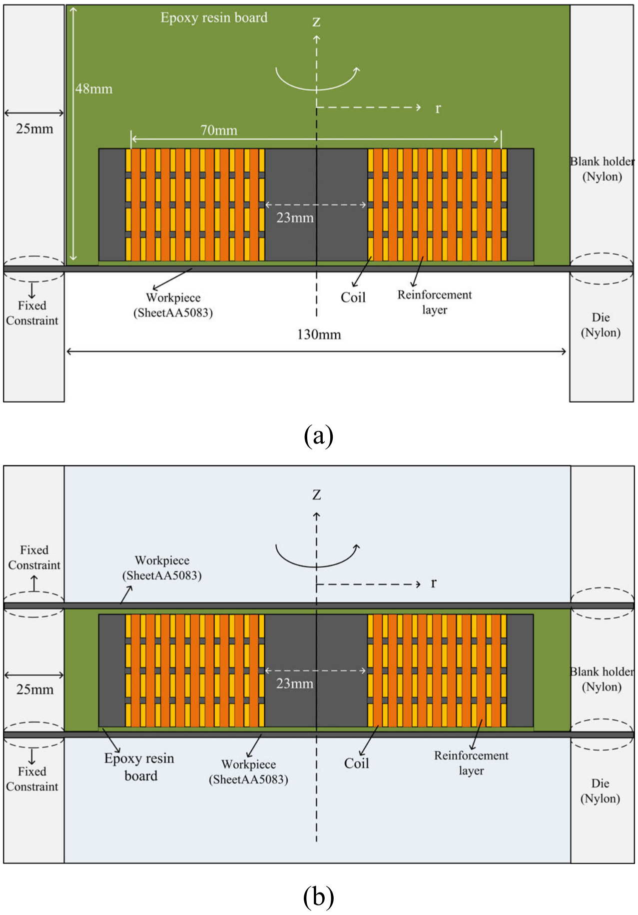

FIGURE 6. Schematic of the metal sheet EMF forming system; (a) single-sheet, (b) double-sheet.

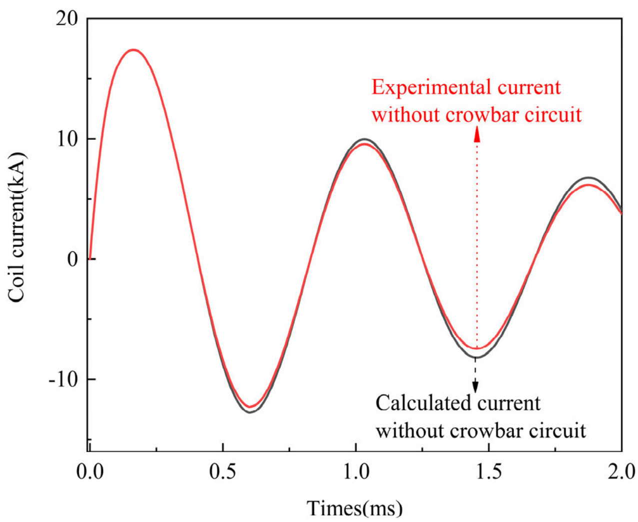

FIGURE 7. Current waveforms obtained from the developed simulation model and the experimental results in [24].

As can be observed from the figure, there is a good agreement of the two waveforms in terms of oscillation and peak values. For both waveforms, the current maximum overshooting is 17.5kA and the rise time is 407.5μs.

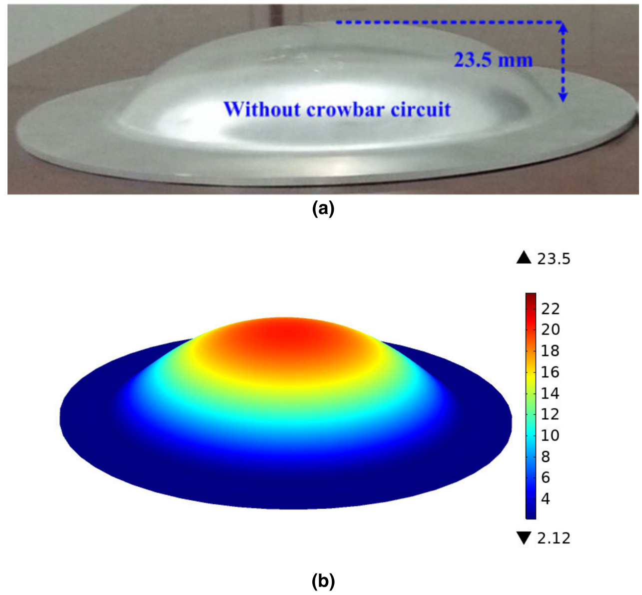

FIGURE 8. Sheet forming profile; (a) experimental results in [24], (b) simulation results in this paper.

Figure 8(a) shows the outline of the sheet obtained using the experimental results in [24] while Figure 8(b) shows the outline of the workpiece as obtained from finite element simulation analysis in this paper. It can be seen that the outlines of the sheet in both figures are pretty similar. However, the maximum deformation obtained by the simulation model is slightly smaller than the maximum deformation obtained using experimental measurement. This may be attributed to the assumption of stationary sheet ends considered in the simulation.

These results reveal that the electromagnetic-structure coupling model established in this paper can effectively simulate the EMF process. Based on this model, the factors that affect the forming efficiency of the double-sheet EMF are investigated below.

V. FORMING EFFICIENCY

Assuming the sheet as rigid body that accelerates due to the generated electromagnetic force, the ratio of the kinetic energy of the sheet to the initial total electrical energy is defined as the forming efficiency. To highlight the superiority of the proposed model, forming efficiencies of no-sheet model, single-sheet stationary model, single-sheet moving model, double-sheet stationary model and double-sheet moving model are analyzed and compared.

Figure 9 shows the system equivalent inductance for the 5 models. The equivalent inductance of the no-sheet model, single-sheet stationary model and double-sheet stationary model does not encounter any change with time due to the motionless of the sheet. Because the presence of the sheet weakens the magnetic field strength of the driving coil, the equivalent inductance of the system with no-sheet is the largest while the equivalent inductance of the system with the double-sheet is the smallest. In the single-sheet or

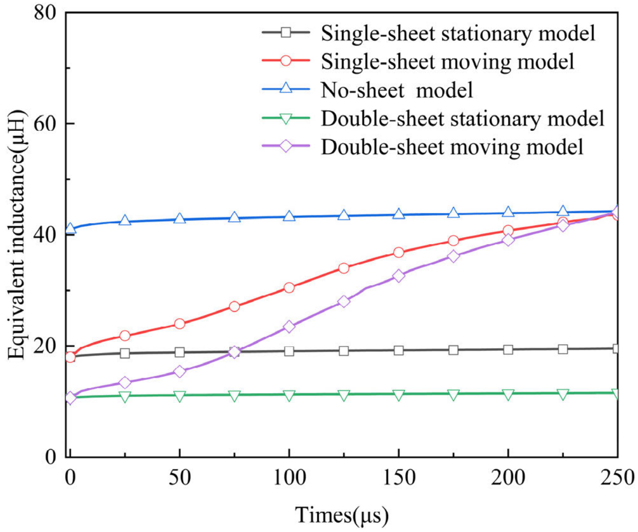

FIGURE 9. System equivalent inductance of five groups of models.

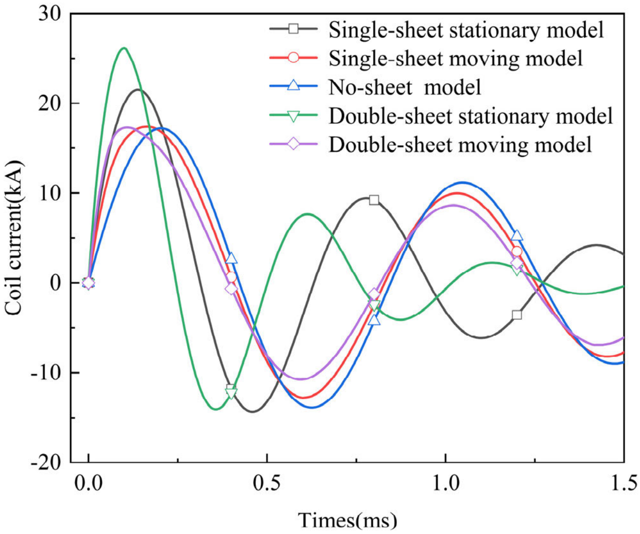

FIGURE 10. Current waveforms of the driving coil in the five models.

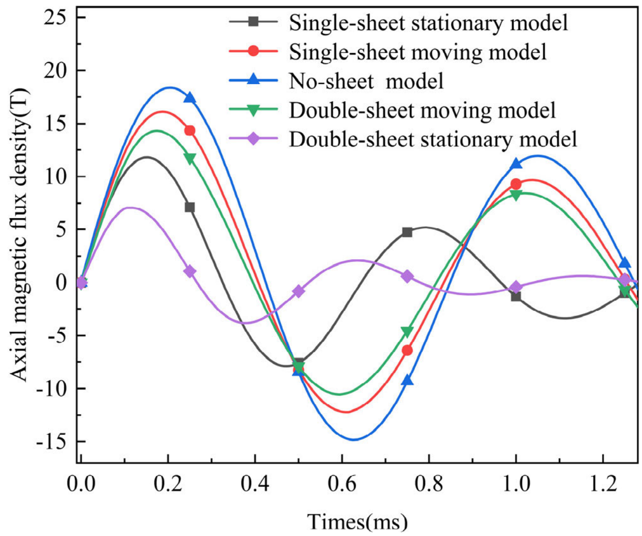

FIGURE 11. Magnetic flux density at the center of the driving coil of the five models.

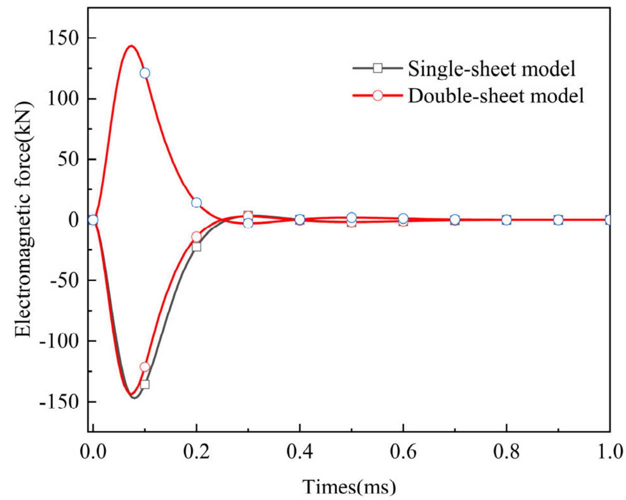

FIGURE 12. Axial electromagnetic force of single and double-sheet moving models.

double-sheet moving models, the distance between the sheet and the driving coil increases with the time and the coupling strength becomes weaker, so the equivalent inductance of the system increases gradually with the time. At $t = 0$ the system equivalent inductance for stationary and moving models is the same in case of single-based and double-based models. In the final state ($t = 250\mu s$) the distance between the sheet and the driving coil is quite far and hence the mutual coupling can be ignored and the system equivalent inductance for single-sheet and the double-sheet moving models are approaching the system equivalent inductance of the no-sheet model.

Figure 10 shows the current waveforms of the driving coil of the five investigated models. Results show that the double-sheet stationary model comprises the largest current (26.1kA) because of its smallest equivalent inductance. The peak current of the single-sheet moving model is 17.4kA with a rise time of $406.2\mu s$, which is in good agreement with the results in Figure. 7.

The magnetic flux densities at the center of the driving coils of the 5 models are shown in Figure 11. For the no-sheet model, the peak value of the magnetic flux density is the largest (18.4T) due to the strong coupling between the driving coil and the sheet. The magnetic flux density gradually decreases with the forming time. The double-sheet stationary model exhibits the smallest magnetic flux density; 7.1T.

The electromagnetic forces on the sheet for single-sheet double-sheet moving models are shown in Figure 12. Results show that the electromagnetic force of the workpiece during the single-sheet EMF is slightly greater than that of the double-sheet EMF. However, since the double-sheet EMF can process two sheets at the same time, its overall efficiency is higher than that of the single-sheet method. Figure 13 shows the speed of the sheet during the two EMF methods. For single sheet EMF, the final speed of the sheet is 124.89m/s with kinetic energy of 1071.7J and forming efficiency of

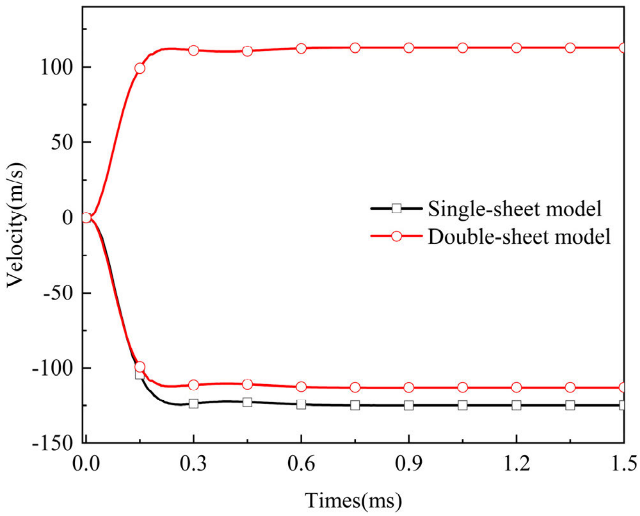

FIGURE 13. Speed of the sheet in EMF based on single and double sheet moving models.

TABLE 2. Forming efficiency for single and double-sheet EMF models.

	Total energy E_0 (kJ)	Kinetic energy E_a (kJ)	Forming efficiency η (%)
single-sheet	10.24	1.503	14.68
double-sheet	10.24	2.164	21.14

10.5%. When EMF is performed on two sheets the final speed of the sheets is 113m/s, kinetic energy of the two sheets is 1754.6J, and the forming efficiency is 17.1%. these results show that using double-sheet EMF improves the forming efficiency of the plate.

The influence of the coil current pulse width on the EMF efficiency of the sheet is investigated by maintaining the total energy of the system at 10.24kJ and changing the capacitance value C_0 and discharge voltage U_0.

The electromagnetic force distributions of the single-sheet and double-sheet EMF models at different discharge current pulse widths are shown in Figure 14. Results show that with the same capacitance value, the peak value of the electromagnetic force experienced by the single sheet is greater than the force experienced by the double sheet. When the capacitor value is 10 μF, maximum electromagnetic force is obtained but for short duration. When the capacitor value is 320 μF, the electromagnetic force is the smallest but with long duration.

In order to achieve better forming efficiency, the relationship between the capacitance value and the sheet speed when the total energy is kept constant is plotted as shown in Figure 15. With the increase of the capacitance value, the speed of the sheet first increases to reach a maximum value then decreases. The sheet speed in the single and double models reaches maximum level at the same capacitance value. For the single-sheet EMF, the maximum sheet speed is 147.9m/s while it is 125.5m/s for double-sheet EMF. Table 2 shows the forming efficiency for the EMF of the single-sheet is 14.68%. This increases to 21.14%, for double-sheet EMF.

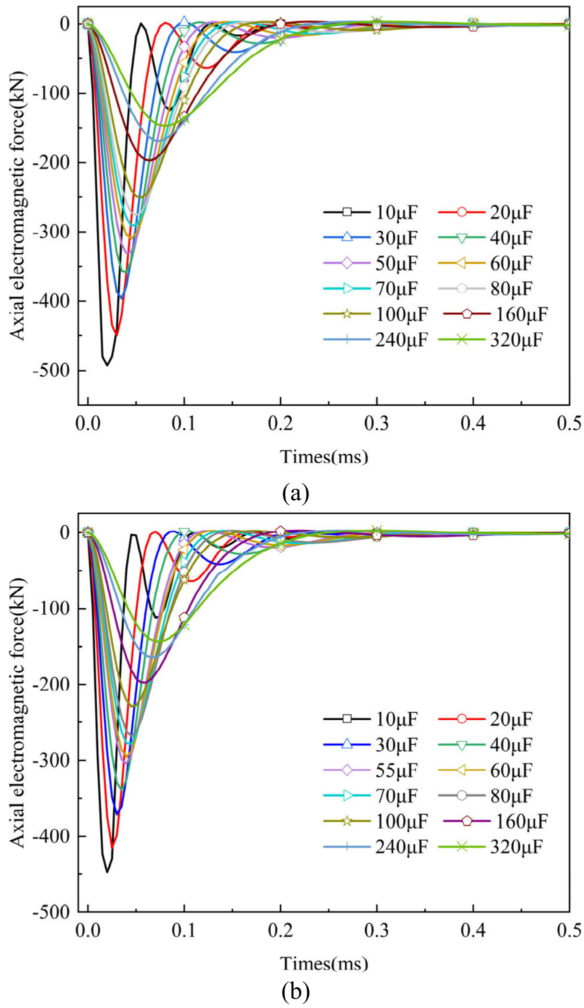

FIGURE 14. Axial electromagnetic force for different discharge pulse widths; (a) single sheet and (b) double sheet.

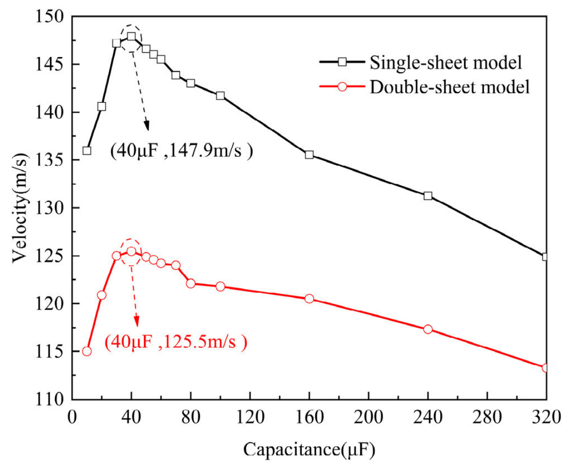

FIGURE 15. The sheet speed at different capacitance values for single and double-sheet EMF models.

Obviously, the double-sheet electromagnetic forming method can effectively improve the forming efficiency.

VI. CONCLUSION

This paper proposes a cost-effective technique to improve the EMF efficiency based on double-sheet model. The performance of the proposed model is compared with other four models to highlight its superiority. Results show that the double-sheet EMF can effectively provide electromagnetic force to form two sheets at the same time with a forming efficiency higher than the single-sheet EMF model. Results also show that when the total discharge energy is kept constant, there is an optimum driving coil current pulse width which maximize the forming efficiency of the double-sheet EMF model. In general, the electromagnetic forming of double-sheet can improve the forming efficiency of the single-sheet model by employing two sheets and without the requirement of extensive modification to the single-sheet EMF method.

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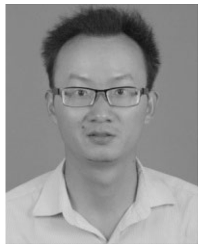

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