International Conference on High Speed Forming

Effect of Workpiece Motion on Forming Velocity in Electromagnetic Forming

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Report content

- Introduction
- Circuit Analysis
- Finite Element Analysis
- Conclusion

Introduction

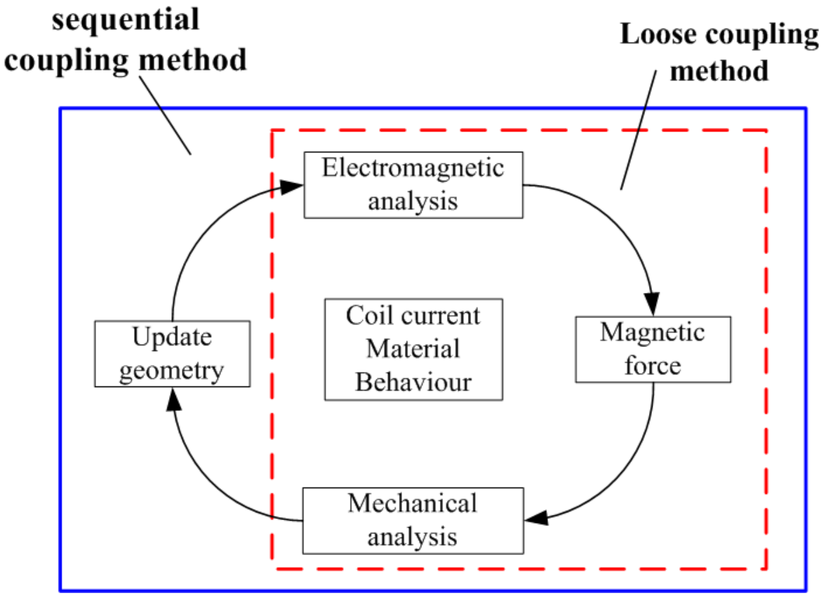

Fig. 1 Finite element method for electromagnetic forming process

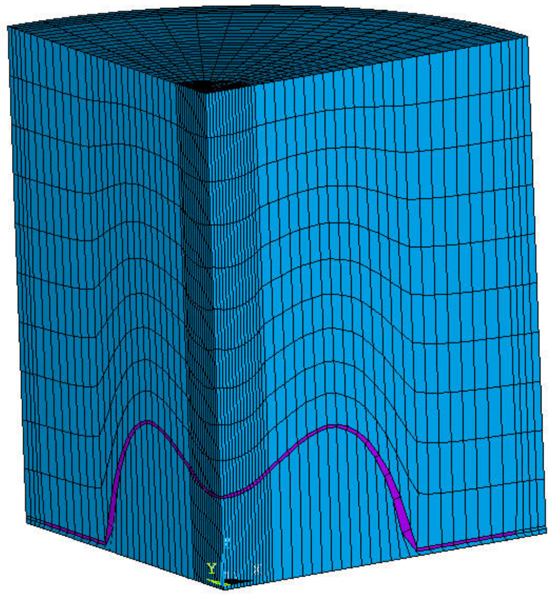

Fig. 2 A sequential coupling model with ANSYS Emag/Ls-Dyna.

The sequential coupling model is quite complicated and the effect of the motional electromotive force on forming velocity is not considered.

Circuit Analysis

Equivalent Circuit of Electromagnetic Forming

In EMF processing, the eddy current in the workpiece is generated due to induced electromotive force and motional electromotive force. The induced electromotive force is generated by the change of the magnetic flux density, while the motional electromotive force is generated by the motion of the workpiece.

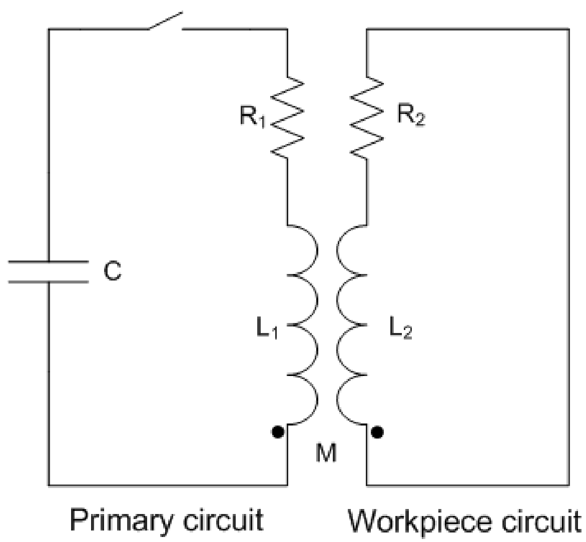

Fig. 3 Equivalent Circuit without considering motional electromotive force

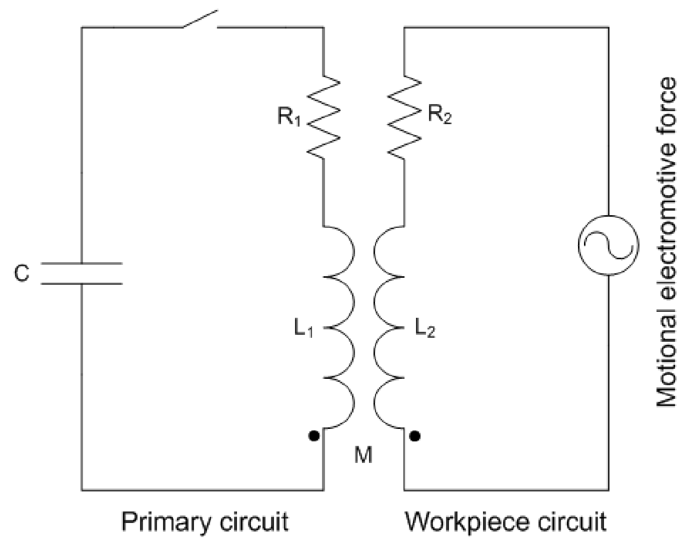

Fig. 4 Equivalent Circuit with considering motional electromotive force

Circuit Analysis

Differential equations of Electromagnetic Forming

$$\begin{cases} i_{10}R_1 + L_1 \dfrac{di_{10}}{dt} + M \dfrac{di_{20}}{dt} = u_c \\ i_{20}R_2 + L_2 \dfrac{di_{20}}{dt} + M \dfrac{di_{10}}{dt} = 0 \\ i_{10} = -C \dfrac{du_c}{dt} \end{cases}$$

Fig. 5 Differential equations without considering motional electromotive force

$$\begin{cases} i_1R_1 + L_1 \dfrac{di_1}{dt} + M \dfrac{di_2}{dt} = u_c \\ i_2R_2 + L_2 \dfrac{di_2}{dt} + M \dfrac{di_1}{dt} + Blv = 0 \\ i_1 = -C \dfrac{du_c}{dt} \\ \dfrac{dv}{dt} = \dfrac{F}{m} = \dfrac{Bi_2 l}{\rho lhd_2} = \dfrac{Bi_2}{\rho hd_2} \end{cases}$$

Fig. 6 Differential equations with considering motional electromotive force

When considering the motional electromotive force, the term of 'BLv' is put in the workpiece circuit.

And the motion equation of the workpiece should be calculated.

Circuit Analysis

Theoretical analysis

Define W as the total energy of electromagnetic energy and the Joule heat：

$$W = Q_C + Q_{L1} + Q_{L2} + Q_M + Q_1 + Q_2 \qquad (1)$$

Differential type of W:

$$dW = Cu_C du_c + i_1 L_1 di_1 + i_2 L_2 di_2 + M i_1 di_2 + M i_2 di_1 + i_1^2 R_1 dt + i_2^2 R_2 dt \quad (2)$$

From the differential equations without considering motional electromotive force we get:

$$u_C = i_1 R_1 + L_1 \frac{di_1}{dt} + M \frac{di_2}{dt}, \quad M di_1 = -(i_2 R_2 dt + L_2 di_2), \quad du_C = -\frac{i_1}{C} dt$$

Substitute into (2): $dW = 0 \quad (3)$

In this case, W is a constant and no electromagnetic energy is converted into kinetic energy.

Circuit Analysis

Theoretical analysis

From the differential equations with considering motional electromotive force, we get:

$$u_C = i_1 R_1 + L_1 \frac{di_1}{dt} + M\frac{di_2}{dt}, \qquad M di_1 = -(i_2 R_2 dt + L_2 di_2 + Blv dt) \quad du_C = -\frac{i_1}{C} dt$$

Substitute into (2):

$$dW = -Blv i_2 dt \quad (4)$$

The electrical energy Q_m due to the motional electromotive force can be calculated by

$$Q_m = -\int_0^t e_m i d\tau = -\int_0^t Blv i_2 d\tau \quad (5)$$

Compared equations (4) and (5), we obtain that *W* decreases because of the motional electromotive force.

Circuit Analysis

Numerical results

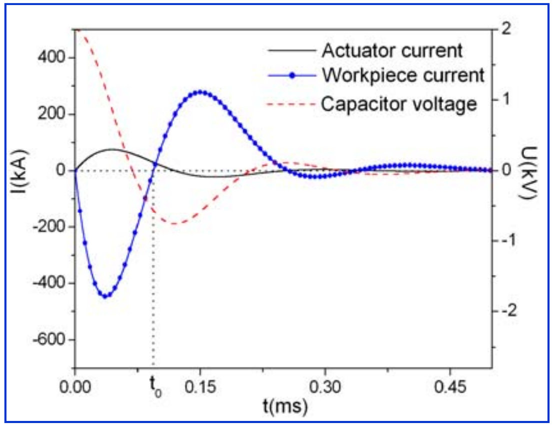

Fig. 7 Results without considering motional electromotive force

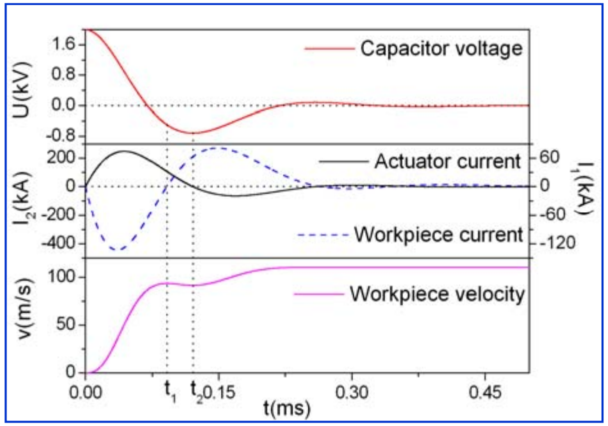

Fig. 8 Results with considering motional electromotive force

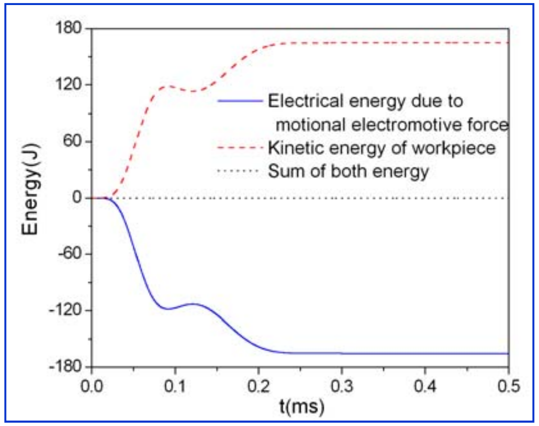

Fig. 9 Relationship between Q_m and kinetic energy.

Q_{sum0}=4000J

$v(t_0)$=98.6m/s

$Q_{sum}(t_0)$=4131.6J

Q_{sum0}=4000J

$v(t_1)$=93.6m/s

$Q_{sum}(t_1)$=3999.9J

$Q_m=-E$

Comparing the results in Fig. 7 and 8, the coil and workpiece peak current is smaller and the time of the first cycle of the current pulse is shorter when considering the motional electromotive force.

Conclusion and Discussion

Conclusion

- The results without considering the motional electromotive force is incompetence due to the law of conservation of energy.
- The electric energy is converted into kinetic energy because of the motional electromotive force.

Discussion

- The magnetic flux density generated by the coil in the workpiece is considered to be uniform.
- The effect of the workpiece displacement on the forming velocity is not considered.

Finite Element Analysis

Physical model and assumptions

The electromagnetic forming process can be divided into two subsequent phases. First, the workpiece is accelerated by the electromagnetic force. Then, the moving workpiece is deformed by the force due to inertia. Four finite element models reflecting different conditions are created to analyse the first phase of the electromagnetic forming process.

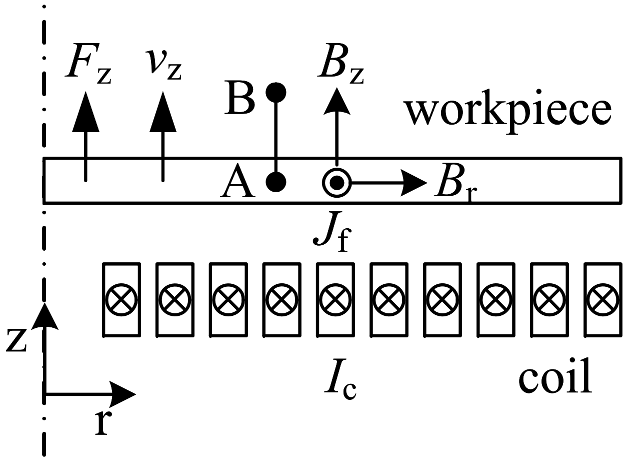

Fig. 10 Electromagnetic sheet metal forming.

Assumptions:

- The current load is a half sine wave with the peak current I_{max} and the pulse width t_c.
- The workpiece is treated as a rigid body in the acceleration process.
- There is no other force except the electromagnetic force.

Finite Element Analysis

Model parameters

Current Pulse	
Peak current I_{max} (kA)	20
Pulse width t_c (μs)	80
Coil	
Material	Copper
Resistivity ρ_c (Ωm)	1.67×10^{-8}
Relative permeability μ_{rc}	1
Cross section (mm×mm)	4×6
Number of turns N	10
Height h_c (mm)	6
Workpiece	
Material	Aluminum
Density ρ_w (kg/m^3)	2700
Resistivity ρ_{ew} (Ωm)	2.83×10^{-8}
Relative permeability μ_{rw}	1
Thickness h_w (mm)	2
Radius R (mm)	50
Distance between coil and workpiece d (mm)	1

Finite Element Analysis

Basic Theory

$$\nabla \times E_{\phi} = -\frac{\partial B_z}{\partial t} + \nabla \times \left(v_z \times B_r \right) \quad (6)$$

$$J_{\phi} = \sigma E_{\phi} \quad (7)$$

$$\nabla \times B = J_{\phi} \quad (8)$$

$$F_z = J_{\phi} \times B_r \quad (9)$$

$$\int_V F_z dV = m a_z, v_z = \int_0^t a_z d\tau, S = \int_0^t v_z d\tau \quad (10)$$

The workpiece is accelerated due to the electromagnetic force, while the motion of the workpiece generates the motional electromotive force reacting on the electromagnetic force as shown in equations (6), (7), (8), and (9). These equations describe the electromagnetic and structural coupling problem of the electromagnetic forming process.

Finite Element Analysis

The axial distribution of the normalized magnetic flux density

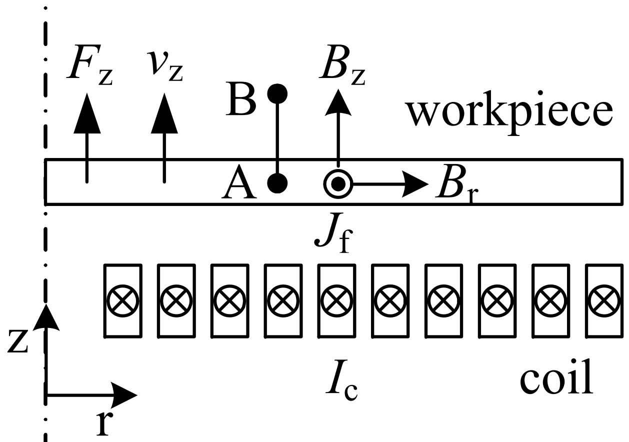

Fig. 10 Electromagnetic sheet metal forming.

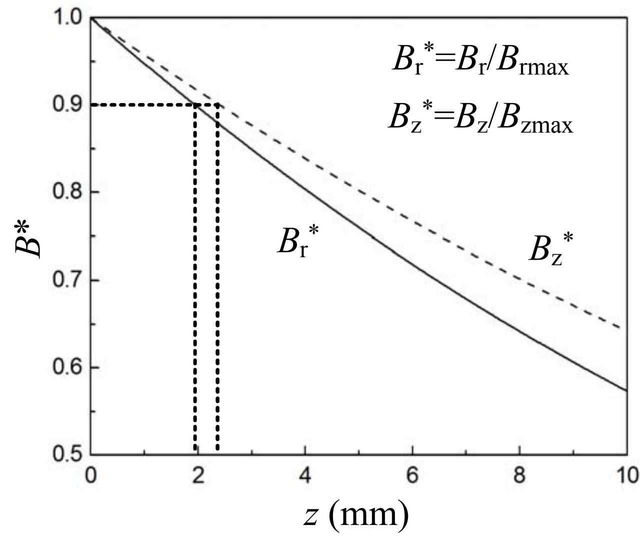

Fig. 11 The axial distribution of the normalized magnetic flux density

The radial magnetic flux density reduces more quickly than the axial magnetic flux density. The normalized radial and axial magnetic flux density drops by 10 % when the workpiece moves about 2 mm away from the initial position

Finite Element Analysis

Four finite element models

Static model

In this model, the workpiece is stationary and the effect of the workpiece motion on the forming velocity is not considered.

$$\nabla \times E_{\phi} = -\frac{\partial B_z}{\partial t} + \nabla \times \left(v_z \times B_r \right) \quad (6-1)$$

Displacement model

The workpiece moves and the effect of the workpiece displacement on the forming velocity is considered in this model.

$$\nabla \times E_{\phi} = -\frac{\partial B_z}{\partial t} + \nabla \times \left(v_z \times B_r \right) \quad (6-2)$$

Finite Element Analysis

Four finite element models

Velocity model

In this model, the workpiece is stationary but the effect of the motional electromotive force on the forming velocity is considered.

$$\nabla \times E_{\phi} = -\frac{\partial B_z}{\partial t} + \nabla \times \left(v_z \times B_r \right) \quad (6-3)$$

Complete motional model

The effect of workpiece displacement and motional electromotive force on the forming velocity is considered simultaneously in a complete motional model.

$$\nabla \times E_{\phi} = -\frac{\partial B_z}{\partial t} + \nabla \times \left(v_z \times B_r \right) \quad (6-4)$$

Finite Element Analysis

Four finite element models

Model Description

- ✓ Static model
- ✓ Displacement model
- ✓ Velocity model
- ✓ Complete motional model

Simulation software

- ✓COMSOL、Flux
- ✓COMSOL
- ✓COMSOL
- ✓Flux

The displacement and velocity models are built by the software COMSOL, while the software Flux is used to simulate the complete motional model. To ensure the correctness of the model, the static model is created by both software.

The static model is a transient electromagnetic model while the complete motional model is a translating motion model.

The velocity model is created by changing the variables of the workpiece subdomain.

Finite Element Analysis

Displacement model

The displacement model is created by the level set method. A cylindrical area with axial length 20 mm is used to take the place of the real workpiece. The material conductivity of the cylindrical area changes with the workpiece displacement to simulate the workpiece motion:

$$\sigma_{\mathrm{w}} = \begin{cases} \dfrac{1}{\rho_{\mathrm{ew}}} \cdots\cdots |z - z_0| < \dfrac{h_{\mathrm{w}}}{2} \\ 0 \cdots\cdots\cdots |z - z_0| > \dfrac{h_{\mathrm{w}}}{2} \end{cases}$$

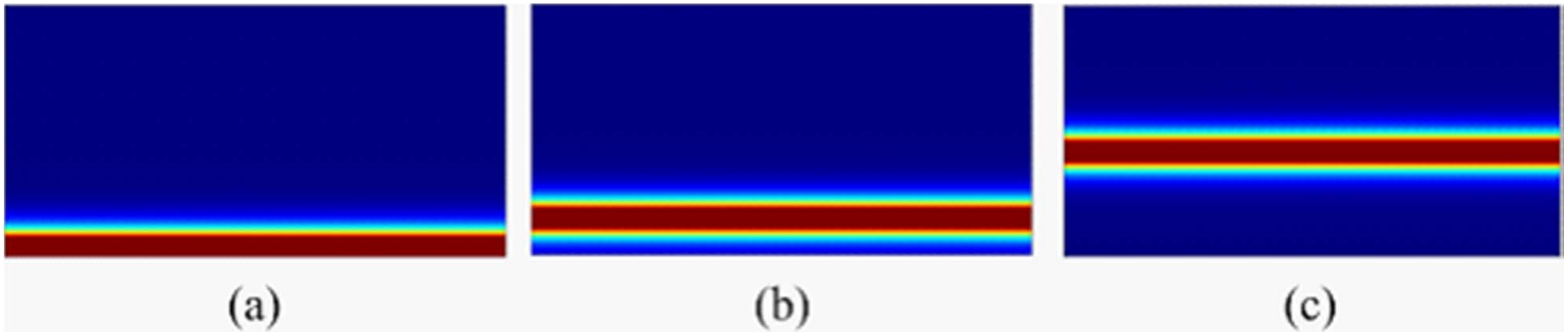

Fig. 12 The material conductivity of the cylindrical area at different times in the electromagnetic forming process. (a) t=0, (b) t=60 μs, (c) t=80 μs.

Finite Element Analysis

Results and Analysis

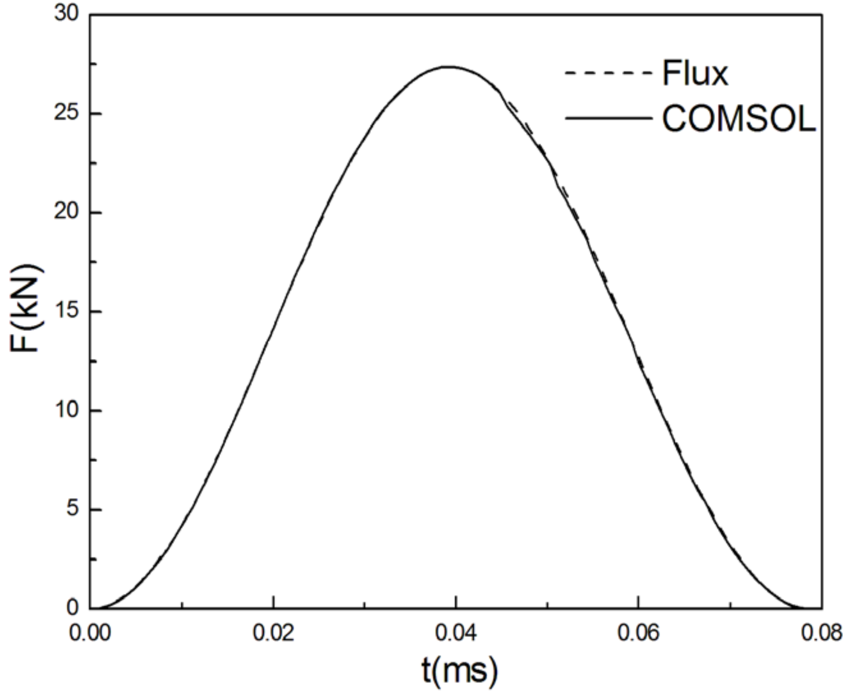

Fig. 13 The electromagnetic force of the static model by both COMSOL and Flux

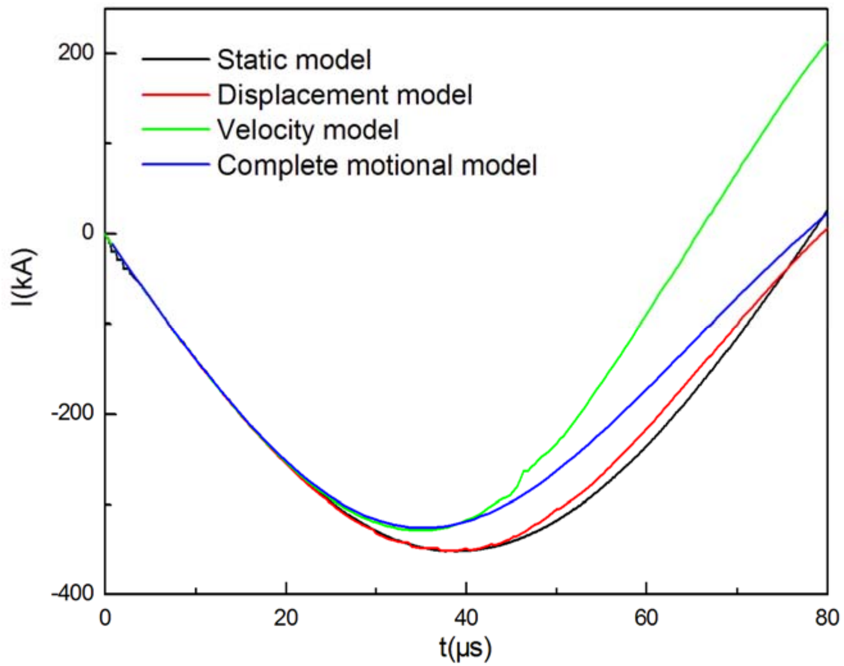

Fig. 14 The eddy current in the workpiece of the four models.

The eddy current in the workpiece is minus. When considering the workpiece displacement or the motional electromotive force, the electric field and eddy current decreases.

Finite Element Analysis

Results and Analysis

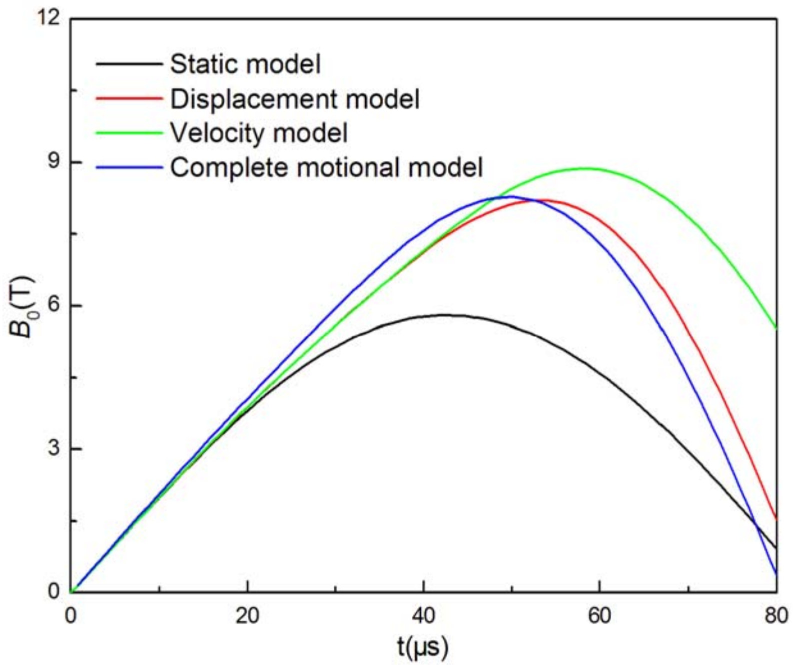

Fig. 15 Magnetic flux density at the center of the coil of the four models.

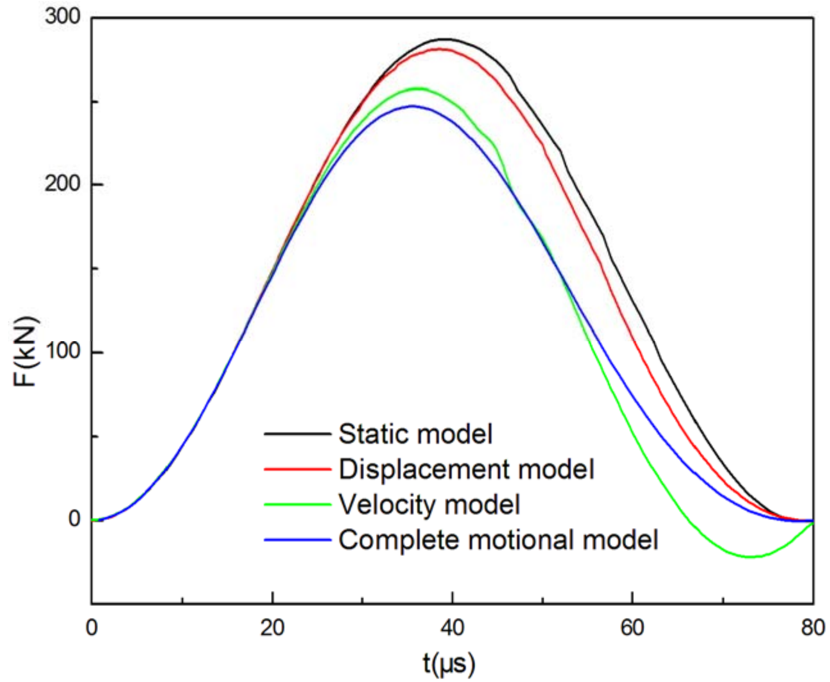

Fig. 16 The electromagnetic force of the four models.

Because of the decreasing of the eddy current, the magnetic flux density at the center of the coil increases, and the electromagnetic force decreases.

Finite Element Analysis

Results and Analysis

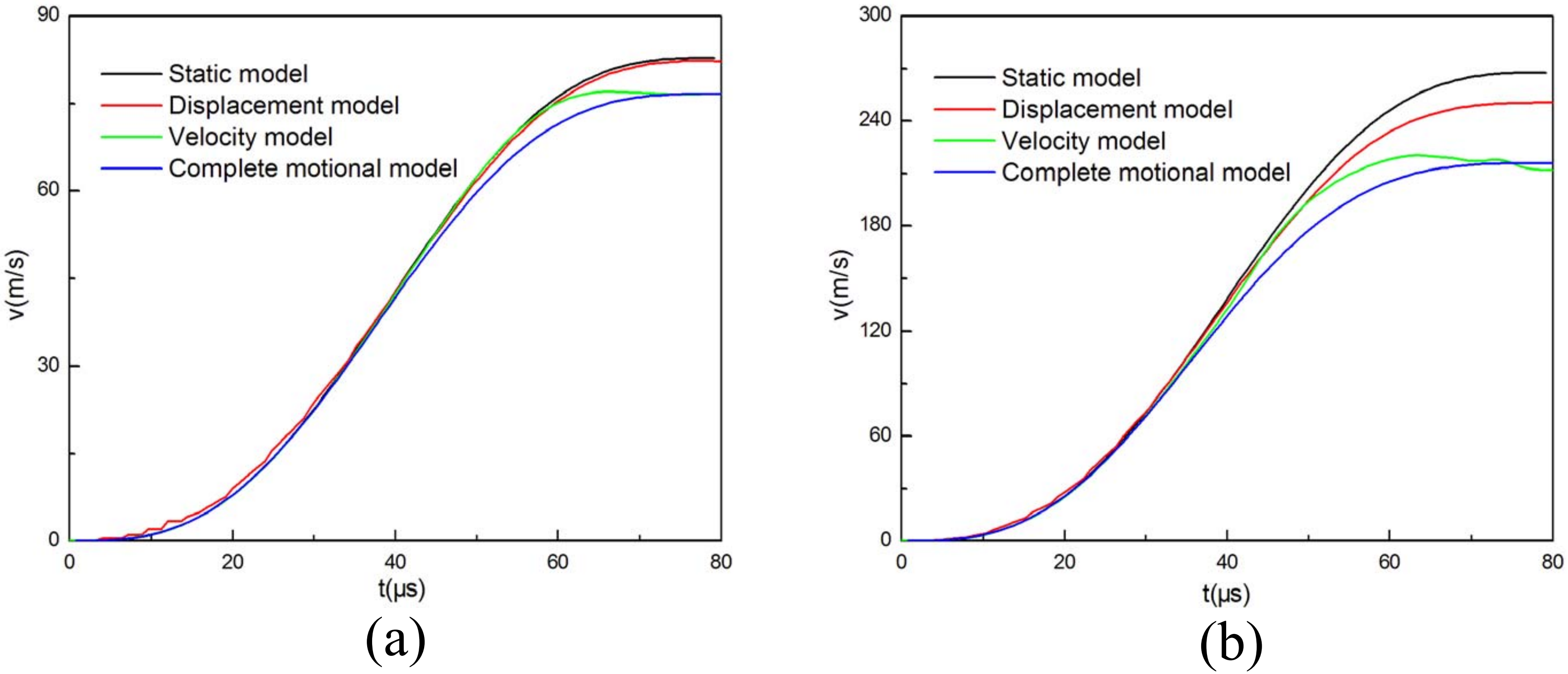

Fig. 17 The forming velocity of the four models at different current. (a) I_{max}=20 kA, (b) I_{max}=36 kA

When *I*max is 20 kA, the results of static model and displacement model almost coincide.

When *I*max is 36 kA, the results of the four models are different.

Conclusion

- The electrical energy is converted into kinetic energy because of the motional electromagnetic force.
- when the workpiece velocity is below 100 m/s, the workpiece displacement has only a small effect on the forming velocity.
- when the workpiece velocity is above 200 m/s, the effect of both the workpiece displacement and the motional electromotive force on the forming velocity must be taken into account in the finite element model of the electromagnetic forming process.

Thank You!