Effect of Workpiece Motion on Forming Velocity in Electromagnetic Forming[*]

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Abstract

The effect of workpiece motion on the forming velocity is analysed by the finite element method. To study the two factors of workpiece displacement and motional electromotive force, a static model, an incomplete motional model and a complete motional model are created. The incomplete motional model is simulated by the finite element software COMSOL, while the complete motional model is simulated by another finite element software Flux. To ensure the correctness of the model, the static model is created by both softwares. For the specific system treated in this paper, the results show that when the workpiece velocity is below 100 m/s, the workpiece displacement has only a small effect on the forming velocity. But when the workpiece velocity is above 200 m/s, the effect of the workpiece displacement on the forming velocity must be taken into account in the finite element model of the electromagnetic forming process.

Keywords

Electromagnetic sheet metal forming, Forming Velocity, Workpiece displacement, Finite element model.

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1 Introduction

Electromagnetic forming (EMF) is a high-speed metal forming technology where the workpiece is deformed by a pulsed electromagnetic force [1]. Compared with conventional metal forming, electromagnetic forming can improve the formability of many metals [2]-[3]. Hence, electromagnetic forming as a novel metal forming technology is widely studied [4]. 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.

J. Unger et al developed a 3D finite element model for the EMF process which consists of a carefully chosen discretization, a data transfer method for both, the electromagnetic loads and the mechanical deformation to utilize an efficient solid shell formulation and a termination criterion for the electromagnetic part of the model [5]. However, the model is quite complicated and the effect of the workpiece motional electromotive force on forming velocity is not considered. Li Qiu et al find that electromagnetic energy is transformed into kinetic energy due to the workpiece motional electromotive force [6]. This model is based on lumped parameters and includes many assumed conditions.

The effect of the workpiece motion on the forming velocity involves both the workpiece displacement and the motional electromotive force. The workpiece displacement causes the electromagnetic force to decrease, while the motional electromotive force hinders the workpiece motion. To analyse the two factors, a static model, an incomplete motional model and a complete motional model are created in this paper. The static and the incomplete motional model are not correct regarding the physics. By comparing the results of the three models, the effect of the workpiece motion on the forming velocity is obtained.

2 Basic Theory

The basic setup treated in this paper and the parameters are shown in Figure 1. The tool coil is a spiral coil and the number of turns is 10. Because of the geometric symmetry, the model is simplified to 2D axisymmetric model. In the electromagnetic sheet metal forming process, the eddy current in the workpiece is generated by the change of the magnetic flux density and the motion of the workpiece:

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

$$J_{\varphi} = \sigma E_{\varphi} \tag{2}$$

$$\nabla \times B = J_{\varphi} \tag{3}$$

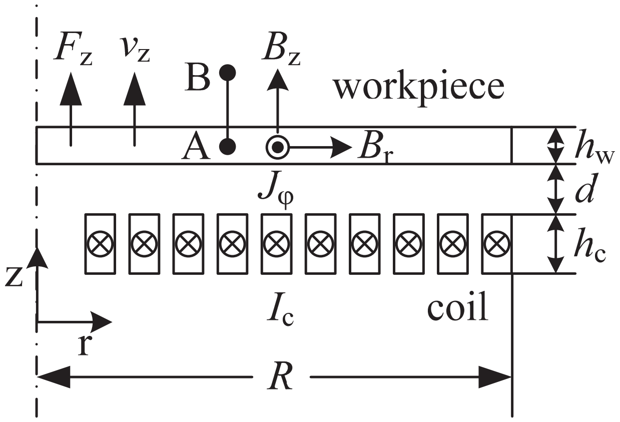


Figure 1: *Electromagnetic sheet metal forming*

E is the electric field, *B* is the magnetic flux density, *v* is the velocity of the workpiece, *J* is the current density, σ is the conductivity of the workpiece and the subscript *r*, φ, and *z* indicate the radial, hoop, and axial components respectively. The two terms on the right hand side of equation (1) reflect the effect of induced electromotive force and motional electromotive force on the electric field respectively.

The electromagnetic force acting on the workpiece is determined by both the eddy current and the magnetic flux density:

$$F_z = J_{\varphi} \times B_r \tag{4}$$

The workpiece is accelerated by the electromagnetic force following Newton's Second Law of Motion and Acceleration:

$$\begin{aligned} &\int_V F_z \, dV = m a_z, \\ &v_z = \int_0^t a_z d\tau, \\ &S = \int_0^t v_z d\tau \end{aligned} \tag{5}$$

Here, m, a_z, v_z, and S are the mass, acceleration, velocity and displacement of the workpiece respectively, t is the pulse width of the electromagnetic force, τ is time as the integral variable. 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 (1), (2), (3), and (4). These equations describe the electromagnetic and structural coupling problem of the electromagnetic forming process.

When the workpiece moves, the magnetic flux density in the workpiece generated by the tool coil decreases because of the increasing distance between the workpiece and tool coil. Hence, the electromagnetic force decreases. Figure 2 shows the distribution of the normalized radial and axial magnetic flux density in the axial direction from point A to B in Figure 1, where B_{rmax} and B_{zmax} are the maximum radial and axial magnetic flux density in the path respectively. 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. This implies that the acceleration process in the electromagnetic forming process should be completed at the 2mm displacement, otherwise the electromagnetic force will severely reduce.

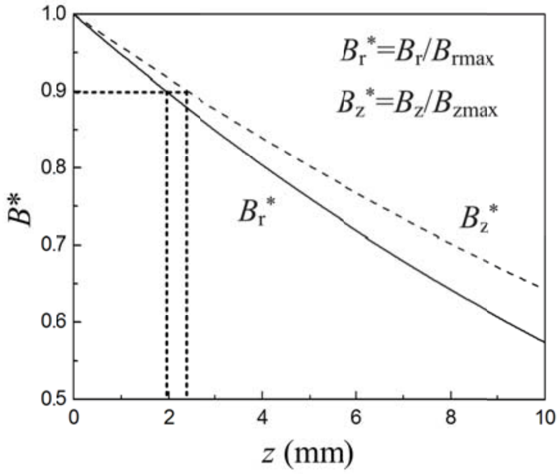


Figure 2: *The axial distribution of the normalized magnetic flux density*

3 Finite Element Models

The electromagnetic forming process can be divided into two subsequent phases. First, the workpiece is accelerated by the electromagnetic force according to the equations in the former section. Then, the moving workpiece is deformed by the force due to inertia. Three finite element models reflecting different conditions are created to analyse the first phase of the electromagnetic forming process in this paper. Table 1 lists the parameters used in the finite element models. In order to simplify the analysis of the effect of workpiece motion on velocity, the finite element models are simplified by the assumptions shown as follows:

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

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

Table 1: *The parameters used in this paper*

3.1 Static model

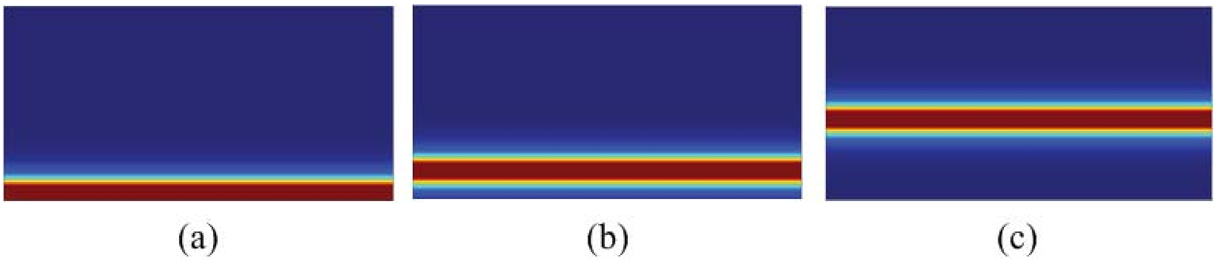
In this model, the workpiece is stationary and the effect of the workpiece motion on the forming velocity is not considered. The eddy current and electromagnetic force in the workpiece are calculated by a transient electromagnetic analysis. The velocity of the workpiece is obtained by equations (4).

3.2 Incomplete motional model

In this model, 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 motion of the workpiece:

$$\sigma_{\mathrm{w}} = \begin{cases} \dfrac{1}{\rho_{\mathrm{ew}}}, & \left|z - z_0\right| < \dfrac{h_{\mathrm{w}}}{2} \\ 0, & \left|z - z_0\right| > \dfrac{h_{\mathrm{w}}}{2} \end{cases} \tag{6}$$

Here, σ_{w} is the material conductivity of the cylinder area, z_0 is the initial position, z is the workpiece displacement at any time which is calculated by equations (5). In equation (6), the area of $\left|z - z_0\right| < \frac{h_{\mathrm{w}}}{2}$ represents the workpiece area. Figure 3 shows the material conductivity of the cylinder area at different times in the electromagnetic forming process. The red and blue area describe the workpiece and air area respectively. The workpiece motion without considering motional electromotive force is simulated by this model.



(a) (b) (c)

***Figure 3:** The material conductivity of the cylindical area at different times in the electromagnetic forming process. (a) t=0, (b) t=60 μs, (c) t=80 μs.*

3.3 Complete motional model

The effect of workpiece displacement and motional electromagnetic force on the workpiece velocity is considered simultaneously in a complete motional model. To simulate the workpiece motion, the upper and lower displacement area and the translating airgap, whose mesh should be remeshing when the workpiece moves, is created. The mesh of the displacement area must be mapped, but the mesh of the translating airgap must be triangular as shown in Figure 4.

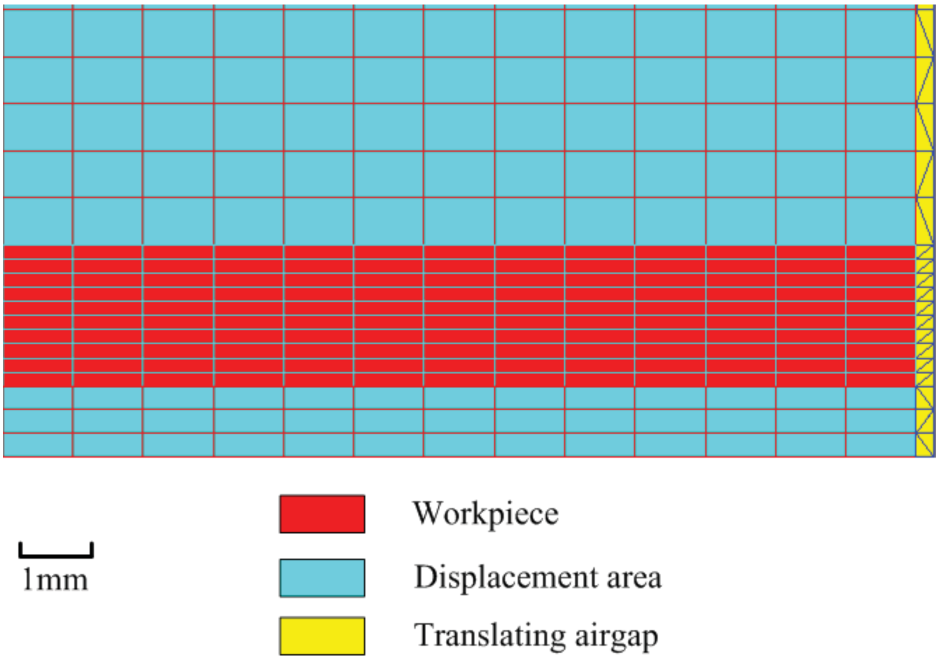


Figure 4: *Finite element model for complete motional model*

4 Results and Analysis

The incomplete motional model is 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. Figure 5 shows that the results of the electromagnetic force calculated by both softwares are almost the same.

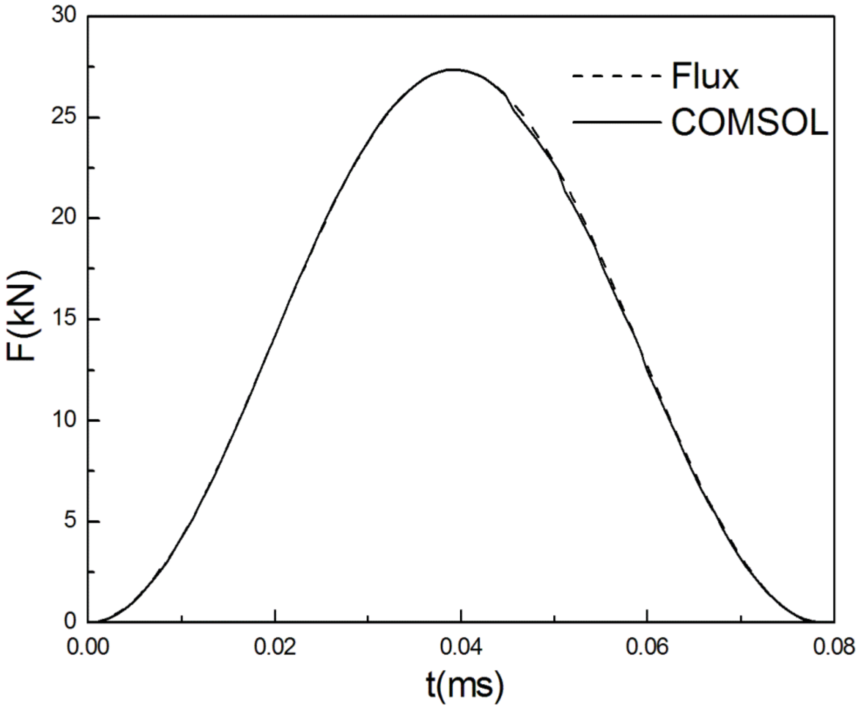


Figure 5: *The results for the electromagnetic force by both COMSOL and Flux*

Figure 6 shows the forming velocity of the three models at different peak current. When $I_{\max}$ is 20 kA, the results of static model and incomplete motional model almost coincide. The workpiece displacement has little effect on the forming velocity when the velocity is below 100 m/s. In this case, the effect of the workpiece displacement on the forming velocity can be ignored. When $I_{\max}$ is 36 kA, the results of the three models are different. That means when the velocity is above 200 m/s, the electromagnetic force decreases quickly because of the rapid movement of the workpiece. In this case, the finite element model of the electromagnetic forming must include the effect of the workpiece displacement on the forming velocity.

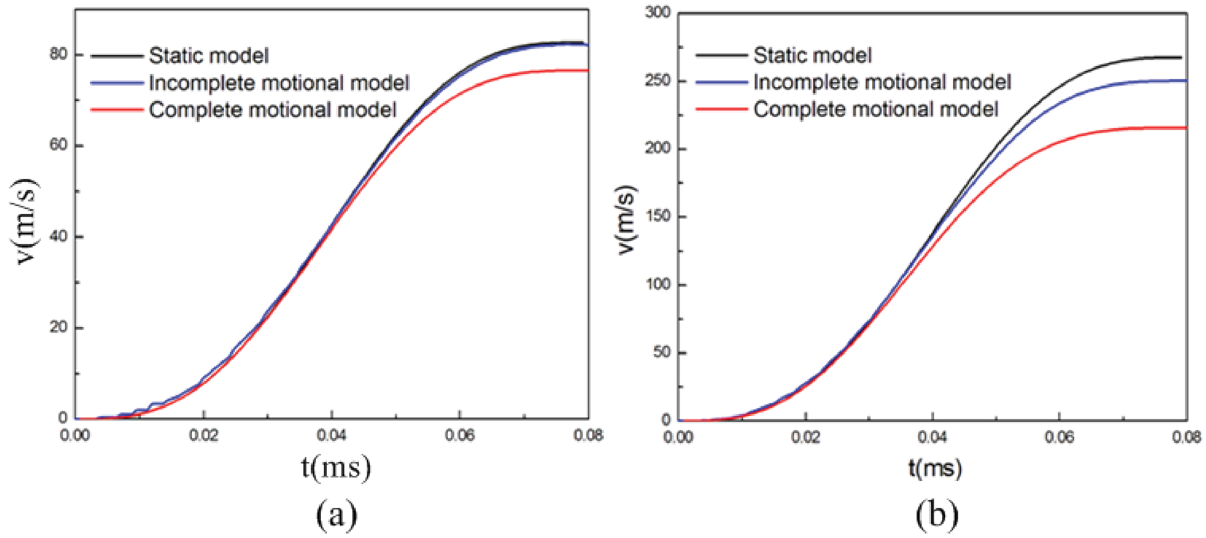


Figure 6: *The forming velocity of the three models at different current. (a)* I_{max}*=20 kA, (b)* I_{max}*=36 kA*

5 Conclusion

To analyse the effect of the workpiece motion on the forming velocity, three finite element models, including a static model, an incomplete motional model and a complete motional model, are built by two different finite element softwares. In the static model, the effect of the workpiece motion on forming velocity is not considered. The workpiece motion without considering motional electromotive force is simulated by the incomplete motional model. The complete motional model, simultaneously considering the workpiece displacement and the motional electromotive force, is simulated by the finite element software Flux. The results show that the effect of the workpiece displacement on the forming velocity must be considered in the finite element model of the electromagnetic forming process, when the workpiece velocity is above 200 m/s in the specific case treated in this paper.

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