A numerical model to simulate electromagnetic sheet metal forming process

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ABSTRACT: The objective of the present work is to build an efficient computational method for numerical simulation and to understand the dynamics of deformation during the electromagnetic forming process (EMF). The finite difference method is used to solve the electromagnetic problem. The magnetic pressure due to the body forces generated by electromagnetic induction is calculated. To verify the results obtained through the finite difference programme, the electromagnetic finite element code FEMM4.0 is used. An axi-symmetric finite element model for electromagnetic free bulging process is developed with the commercial finite element code ABAQUS/Explicit. The magnetic pressure calculated is applied as a loading condition via a user subroutine VDLOAD to model the high rate deformation of the work piece. Results concerning magnetic fields and plastic deformation of the work piece are presented. A good agreement is found between the numerical results from finite difference method and FEMM4.0. The finite element predictions are also in agreement with the experimental results.

Key words: Electromagnetic forming, Finite elements method, Free bulging process

1 INTRODUCTION

In electromagnetic forming process (EMF), magnetic pressure is used for the deformation of electrically conductive metals. Magnetic pressure is developed as a result of the interaction between the transient currents of high intensity between adjacent conductors. The magnetic field in the coil produced due to the discharge current creates eddy currents in the nearby work piece that lasts only for a few microseconds [1]. The resulting eddy current developed in the work piece flows in the opposite direction as to the discharge current which causes the mutual repulsion between the work piece and the forming coil. This pressure is large enough to deform the work metal beyond the elastic yield strength; thus produces the permanent deformation of the work piece at very high strain rates [2].

At present, a significant emphasis on developing reliable numerical methods for the simulations of the process is demanded for the profitable industrial application of EMF. The numerical analysis of the EMF process comprises of two specific problems: an electromagnetic problem and the mechanical problem including the action of magnetic pressure. In this paper principles and basic equations of both these problems are presented. The finite difference code is developed [3] to numerically solve the electromagnetic problem, based on the assumption that the velocity of the work piece has been neglected [4]. Furthermore FEA software FEMM4.0 [5] is used for the verification of the in-house finite difference code. The mechanical problem is solved with the commercial finite element code ABAQUS/Explicit. Finally the finite element predictions are compared with the experimental results of Takatsu et al. [6].

2 NUMERICAL MODELLING OF SHEET METAL FORMING

2.1 *Electromagnetic model*

Typically an electromagnetic problem consists of calculating the basic circuit parameters. Manea et al. [4] demonstrated that in the EMF process the velocity term comes into significance only if the work piece velocity is of the order of 10^7 *m/s*. Since the deformation process during the EMF takes place in a few microseconds the velocity is below the values for which the velocity term may affect the magnetic field during the process [4]. Thus propagation of electromagnetic field within a coil-work piece-air system can be defined by quasi-stationary Maxwell's equations. In cylindrical coordinates system the electromagnetic field density

B is given as:

$$-\frac{1}{\mu_0\sigma_w}\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{\partial^2}{\partial z^2}-\frac{1}{r^2}\right)B_r+\frac{\partial B_r}{\partial t}=0$$

(1)

$$-\frac{1}{\mu_0\sigma_w}\left(\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{\partial^2}{\partial z^2}\right)B_z+\frac{\partial B_z}{\partial t}=0$$

While the current density is given as:

$$J_\theta=\frac{1}{\mu_0}\left(\frac{\partial B_r}{\partial z}-\frac{\partial B_z}{\partial r}\right) \quad (2)$$

Solving the above equations yields the two components of the electromagnetic force as:

$$f_r=J_\theta\cdot B_z$$

(3)

$$f_z=-J_\theta\cdot B_r$$

The corresponding magnetic pressures are evaluated by integration and are defined by:

$$P_r=\int_{z=0}^{z=h} f_r\,dz$$

(4)

$$P_z=\int_{z=0}^{z=h} f_z\,dz$$

where *h* is the thickness of the sheet.

An explicit scheme of time derivative is used for the solution. The finite difference method used to solve these equations is based upon the construction of a grid by descretizing the work piece into cells of size $\Delta r\times\Delta e$. The magnetic field is obtained for each increment knowing the current position of the work piece. The algorithm of our finite difference code is as follows: in the first step the magnetic field density within the sheet is computed [equ. (1)]. Then the eddy current, the body forces and the magnetic pressures are calculated [equ. (2-4)]. We used three different grids, *4*x*110*, *4*x*170* and *6*x*220* to model the work piece in order to study the influence of the meshing on the magnitude of the magnetic field. Preliminary verifications [3] of the effects of the gridding were found to be in satisfactory agreement with the experimental results, details of which are beyond the scope of this paper.

2.2 Mechanical Model

Takatsu et al. [6] performed their tests with a *5* turns flat spiral coil connected to a capacitor bank of capacitance of $40\ \mu F$. The initial charging voltage of the capacitor bank is equal to *6 kV*. The initial gap *dg* between the sheet and the coil is *1.6 mm*. The mechanical problem consists of modeling the material A1050 aluminium alloy for electromagnetic forming process. The geometry used was selected in accordance with the experimental work [6]. An axi-symmetric configuration is adopted to model the work piece and the tools; this simplification is used because of the symmetrical distribution of forces and reduces the computing cost without affecting the results. ABAQUS/Explicit code was used for the simulations; the work piece is modelled as deformable part while the die and blank holder are considered to be planar rigid [7].The system and material parameters are reported in Table 1.

Table1. System and material parameters of the simulation

Coil	Number of turns	5
	Maximum radius	40 mm
	Charging voltage	6.0 kV
	Circuit inductance	2.86 µH
	Circuit resistance	25.5 $m\Omega$
Work piece	Radius	55 mm
	Thickness	0.5 mm
	Density	2.75x10^3 kg/m^3
	Young's modulus	80.7 GPa
	Poisson's Ratio	0.3
	Conductivity	36 MS/m
Die	Radius	40 mm

Similar meshing of the work piece were employed as used for the finite difference calculations to study the effects on deformation. To predict the inertial and dynamic effects of magnetic pressure acting on the work piece during the forming process, dynamic/explicit time integration scheme is used in our simulations. The simulation time is considered to be $270\ \mu s$ conforming to the experiments [6]. The magnetic pressure calculated through the finite difference method is introduced as a mechanical pressure distributed at the lower surface of the sheet via a subroutine VDLOAD in ABAQUS/Explicit. Classical rate-dependant hardening Holloman type constitutive power law is used.

$$\sigma=\sigma_0\left(\varepsilon^p\right)^n D\left(\dot{\varepsilon}^p\right)^m \quad (5)$$

where $\dot{\varepsilon}^p$ is the effective plastic strain rate, *m*, *n* and *D* are the rate dependant exponent and multiplying factor respectively and σ_0 is material constant.

3 RESULTS

Figure 1 shows the temporal variation of the discharge current. The discharge current is a damped sinusoidal function given as:

$$I(t)=I_0\,e^{-t/\tau}\sin\omega t \quad (6)$$

where I_0 represents the maximum intensity of the discharge current, τ the damping coefficient (it characterises the exponential decrease of the current) and ω the angular frequency. The first peak is at *17.5* μs and the second peak is observed at *87.5* μs.

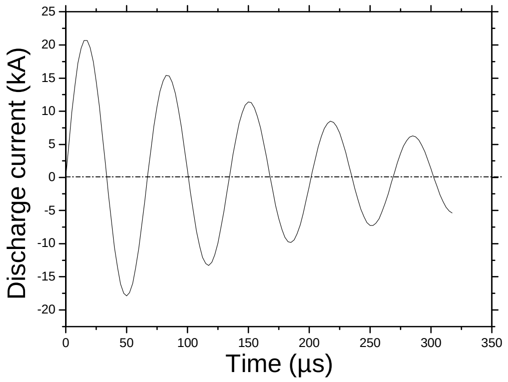
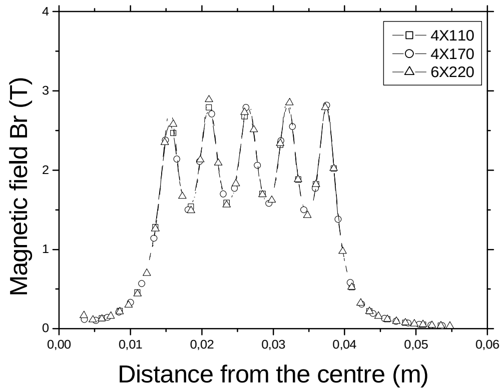
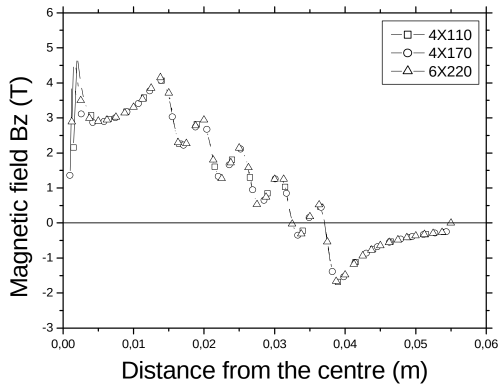


Fig. 1. Evolution of the intensity of the discharge current

The components of the magnetic flux densities calculated with finite diffence method are shown in the figure 2 at *17.5* μs for the three grids used.



(a) Br

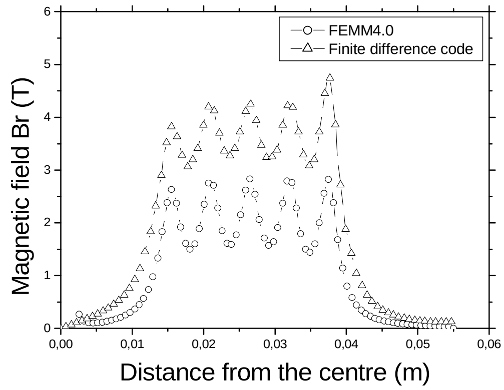


(b) Bz

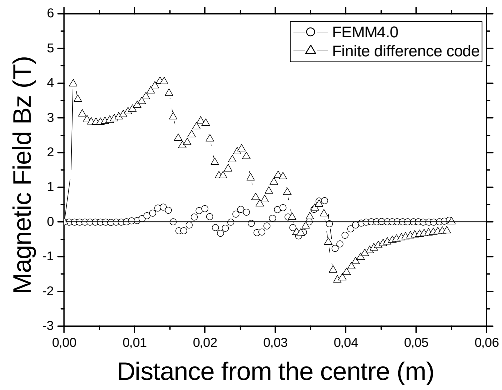
Fig. 2. Magnetic field density *B*

It is observed that there exists a very small variation between the results for the different meshing of the sheet surface. This is due to the very small thickness. The effects of the variations of gridding become significant as the thickness of the sheet is increased [3], which is defined as the skin depth effect during the electromagnetic forming process. The magnitude of the magnetic field density decreases as the time is elapsed from the first peak of the discharge current to the second.

In order to validate the finite difference code, the deformed geometry of the work piece at different time steps from ABAQUS/Explicit simulations were then used to develop the axi-symmetric electromagnetic finite element model in FEMM4.0. In order to study the effects of sheet movement during the process the geometry of the sheet is updated at different time intervals and the results are then compared with the finite difference calculations. The comparison between the finite difference calculations and FEMM4.0 at *17.5* μs is presented in figure 3. The final results are presented when we have considered the grid configuration of *4* elements along the thickness *(e)* direction and *170* along the radial *(r)* direction. The FEMM4.0 results are in agreement with the finite difference code, thus validating the results from the simulations of ABAQUS/Explicit.



(a) Br at 17.5 μs



(b) Bz at 17.5 μs

Fig. 3. Comparison between FEMM4.0 and Finite Difference results for Magnetic field density *B*

In figure 4 the profiles of the sheet for the mesh configuration of *4*x*170* is presented. It has been observed that the deformation of the sheet is more pronounced at the centre of the disk than at the corners. This is due to the maximum magnetic pressure exerting at almost ½ radius of the disc and the surroundings moved later because of the lower pressure. The FEM predictions are in good agreement with the experimental profiles.

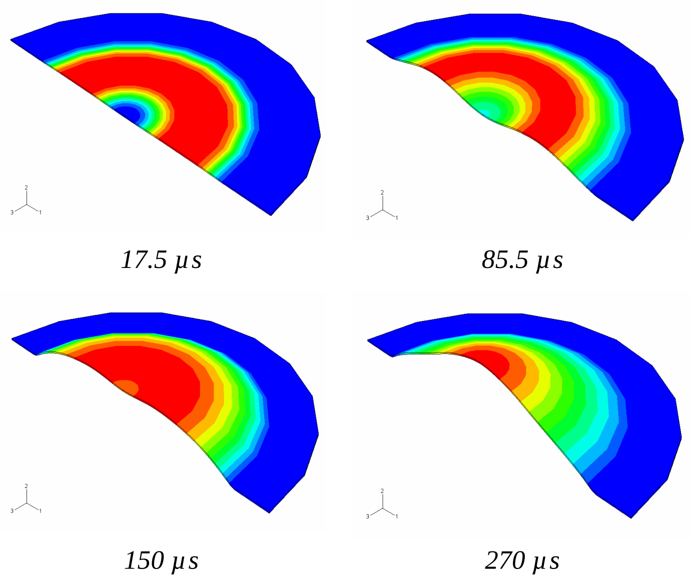


Fig. 4. ABAQUS/Explicit predictions of deformed sheet

The deformations of the sheet are shown in figure 5. The profiles during the forming process are similar to the experimental measurements of Takatsu et al. [6]. Solid lines are numerical results while scattered points are the experimental results [6]. The profiles conforms to the experimental results [6], however there exists a slight variation of the sheet deformation. This variation may have occurred because of the use of a simple and approximate material constitutive plasticity model. This model may account for the strain rate dependency but to accurately predict the dynamic deformation during the EMF process, more adept constitutive model may needed to be applied.

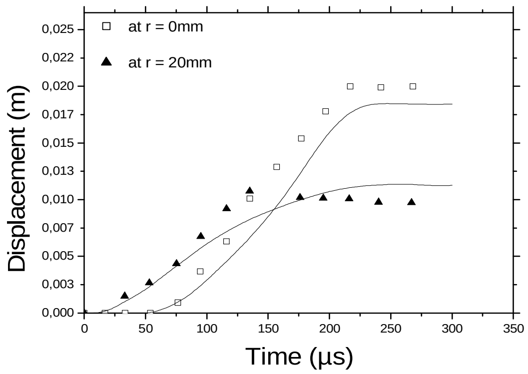


Fig. 5.Vertical deflection U2 of the sheet at radii 0 mm and 20 mm as function of time

4 CONCLUSIONS

In the present paper the basic aspects of electromagnetic sheet metal forming process are numerically simulated solving two separate problems. The first one enfolds the computation of electromagnetic parameters that yield the electromagnetic pressure using a finite difference code. The second aspect deals with a finite element simulation implementing the results from the finite difference code in an axi-symmetric model. The predicted results are in good agreement with the experimental ones [6]. Influence of different mesh sizes was also investigated. It was observed that due to very small thickness of the work piece, the mesh size effects are of minimal nature which may be attributed to the skin depth of the work piece. The verification of the finite diference code was carried out using FEMM4.0. The finite difference code has then been introduced in the commercial FE code ABAQUS/Explicit via a user subroutine VDLOAD for simulations. The FE predictions are in good agreement with the experimental results [6]. Further work may include implementation of rate-sensitive material constitutive models such as Jonhson-Cook [8] to study the dynamic high speed electromagnetic forming process.

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