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Research Paper

STUDY OF THE SYSTEM CHARACTERISTICS ON THE PERFORMANCE OF THE SHEET METAL ELECTROMAGNETIC FORMING

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In Electromagnetic Forming (EMF) process a sheet metal is situated close enough to a working coil. By discharging the initiallycharged capacitor bank through the coil the workpiece is repelled. This repulsion force originates from the interaction of two magnetic fields; consequently sheet metal forming can be achieved when the workpiece strikes the die.The output of an EMF system strongly depends on the characteristics of the workpiece and electrical parameters. Displacement of the workpiece influences the behavior of the system and the frequency of the applied current affects the performance of the system. Geometrical characteristics of the workpiece which determine the mass and effective area of the workpiece have also considerable effect. The objective of this paper is to study the effect of these parameters on the output of an EMF system. Simulations based on Finite Element Method (FEM) are used to study the (EMF) process and investigate the performance of the system by changing effective parameters. Based on carried out simulations the best configuration of a sheet metal forming system is suggested, which enhances the efficiency of the system and the desired output is achievable.

Keywords: Electromagnetic forming, Numerical simulation, Discharge current, Workpiece characteristics

INTRODUCTION

Electromagnetic forming is a metal working process that relies on the use of electromagnetic forces to deform metallic workpieces at high speeds. Impulse electromagnetic forming is a powerful and effective high-rate forming technique that possesses a number of advantages over conventional methods of metal forming such as high tidiness, cost-efficiency, productivity and repeatability. It also provides good control over different parameters of the system,and since this process occurs at high speeds this technique possesses some considerable and natural characteristics which contribute to its wider applications in industry. Many industries,

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ranging from aerospace to biomedical, have taken interest in employing new techniques to fabricate parts to save costs and time (Masoomi *et al.*, 2015). With respect to lightweight constructions, especially in the field of automotive engineering (Parka, 2005), the forming of materials like aluminum and magnesium alloys gains importance. This even may help to reduce the harmonic losses I order to lower the power systems local marginal prices (Milad *et al.*, 2014). The EMF can also be studied to determine its effect on the ohmic resistance of the transmission and distribution level apparatus, which may affect the grid connection in smart grids as an example (Milad *et al.*, 2012).

There are different ways to control the output of an EMF system. Some of these are determined by the applied current which is actually the result of the other parameters such as initial voltage and capacitance of the capacitor bank and also the ohmic resistance of the circuit especially when there are fault current limiters in the network (Sarfi, 2014). Another important factor which must be considered is the frequency of the applied current. On the other hand, there are some effective parameters that are determined by the geometry of the system and once the system is designed, it is not easy to vary them, such as the shape of the coil or thickness and area of the workpiece which contributes the mass of the workpiese.

In order to facilitate the analysis of an EMF system, itcan be divided into two consecutive parts, electrical and mechanical parts. The electrical step starts with the discharge of the capacitor banks through a coil and ends by repelling the workpiece.

The process of deforming the workpiece, resulted by colliding workpiece and the die, is considered as the mechanical step. Mechanical step is not the purpose of this paper. Final velocity of the workpiece achieved by discharging the capacitor bank is considered as the output of the electrical step of the system, and the aim is to improve or increase this parameter. As a matter of fact, since the final velocity of the workpiece represents the kinetic energy of the workpiece which is the amount of effective energy transferred from initial energy stored in the capacitor bank, it can be used also, as a parameter that demonstrates the efficiency of the system. Besides, higher velocity of the workpiece results in better deformation when it hits the die. As a result, in order to achieve better results, the energy transferred to the workpiece or equivalently the velocity of the workpiece must be as high as possible.

The knowledge of reliable material parametersand optimum system characteristics are essential requirement for appropriate design of an EMF system, thus it can be guaranteed that this technique can be utilized in industry efficiently.Also thorough understanding of the EMF process gives the designer a comprehensive control over performance of the system, while changing the system performance after it is built is not an easy task.

It must be noted that in tubular EMF, in which a cylindrical coil is located inside or outside the workpiece, the workpiece is not accelerated. Due to symmetry of the system, exerting force to the workpiece and deformation of the workpiece occur simultaneously. Depending on the location of the workpiece inside or outside the coil, it contracts or expands respectively.

In order to examine this process analytically some numerical simulations based on Finite Element Method (FEM) have been performed (Kleiner and Brosius, 2001; Mamalis *et al.*, 2005; Unger *et al.* 2006; and Sarfi *et al.*, 2014). The time step and resolution of meshes should be adjusted to decrease the error in final results (Masoomi, 2015). Different researches have focused on different aspects of a tube forming system, such as the length, the ratio of height to diameter of the coil, the radial relative between the coil and the workpiece and the effects of field-shaper (Oliviera *et al.*, 2005; and Kore, 2015).

In this paper different effectual parameters on performance of the system, specially the velocity of the workpiece are studied. These parameters include geometry of the workpiece and the applied current characteristicsand also the interactions of these parameters are investigated. To perform numerical simulation, multiphysics software has been exploited to calculate the magnetic pressure distribution applied on the workpiece during the impulse of EMF process and also the force exerted to the workpiece and consequently the final velocity of the workpiece. Finally in order to achieve higher efficiency and better performance, optimum parameters and characteristics of the EMF system is illustrated.

BASIC FORMING PRINCIPLE

The process of an EMF system is based on two conductor located close enough and carrying currents in opposite direction, which leads to repulsion force. The primary current is result of discharging a capacitor bank through a working coil. Consequently a highly time-varying magnetic field is generated in the space between the coil and the workpiece, which also penetrates the workpiece. Therefore induced currents or eddy currents are produced inside the workpiece. According to Lenz's law the direction of these induced currents are in such a way that oppose the variation of the magnetic field resulted by primary current. The interaction of these two currents, lead to repulsion force that causes the workpiece to accelerate and hit the die. If the velocity of the workpiece at the moment of hitting the die is high enough that the produced stress exceeds the yield point of the workpiece, the workpiece undergoes a permanent deformation according toshape of the die. The amount of initial stored energy in the capacitor bank which is transferred to the workpiece represents the efficiency of the electrical step of an EMF system. Therefore the efficiency can be defined can by Equation (1).

$$\eta = \frac{\frac{1}{2}mv^2}{\frac{1}{2}CV^2} \quad ...(1)$$

Magnitude of the generated electromagnetic force is dependent on geometric parameters of the system construction as well as the electrical parameters. According to faradays law, the generated eddy currents in the workpiece are determined by the variation of the primary current. Faradays law can be seen in Equation (2).

$$\varepsilon = -\frac{d\Phi_m}{dt} \quad ...(2)$$

Φ_m is the magnetic flux and is proportional to the primary current. On the other hand, the force exerted to the workpiece, is determined by the magnitude of the primary current and that of the eddy currents. Consequently, a great and highly time varying current is needed to achieve desired result which is precise deformation of the workpiece. This fact illustrates the essence of the pulse power system.

A typical EMF system consists of a capacitor meant for storing energy, a fast acting switch which should be fast enough to supply the required rise time of primary current, the acting primary coil which creates the magnetic pressure. The coil parameters and workpiece characteristics determine the performance of the EMF system.

The configuration of the EMF system used in this paper for simulations is shown in Figure 1. According to the symmetric characteristic of the coil and the workpiece, 2D axial symmetry simulations were applied to study theEMF system. This configuration consists of a working coil and a workpiece.The dimensions of the flat coiland the parameters of the workpiece are given in Table 1. Electrical parameters of the applied system are also included in this table.

The coil has 12 turns and it should possess good electrical and mechanical properties. As it will be shown, its ohmic resistance has a great influence on performance of the EMF

Figure 1: 2D Axial Symmetrical Configuration of Moving Sontact and Coils

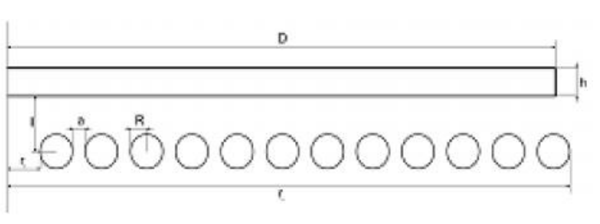


Table 1: The Input Data of the Model

Coil	
Material	**Copper**
r_i(mm)	2.6
r_o(mm)	43.65
R(mm)	1.25
a(mm)	1
Workpiece	
Material	**Aluminum**
l(mm)	8.75
D(mm)	42.4
h(mm)	3
Electrical Parameter	
W(kJ)	6
C(μF)	150
R(Ω)	0.05
f(Hz)	7500
I_{max}(kA)	48
t_{rise}(ηs)	10

system. Also the coil experiences the exact force exerted to the workpiece, therefore it should be able to withstand this stress, since it is not intended to operate only one time, although a practical EMF system has limited life time. Therefore copper seems to be a proper choice.

Aluminum and Magnesium are good materials to be used in an EMF system. Because their conductivity is high enough for eddy currents to be generated and their mechanical characteristics such as mass and ductility are suitable for an EMF system, especially aluminum because it is widely used in automobile industry which is used in this paper as the material of the workpiece for simulations.

ANALYSIS AND SIMULATIONS RESULTS

In this section different effective parameters of an EMF system are studied. Some of them come from the characteristics of the applied current such as frequency and the resistance of the circuit, and the others are related to the geometry of the system.

ELECTRICAL PARAMETER

Frequency is the first parameter of the applied current investigated in this study. It affects the performance of the system in different ways. First, it determines the duration of the impulse of current. Therefore, the greater the frequency, the longer the workpiece experiences electromagnetic force. On the other hand, by increasingthe frequency, the rise time of the applied current decreases and consequently, the amplitude and rate of variation of the primary current rise. This leads to a better performance of the system. In order to compare these two opposite effects, analytical solution is presented. First, final velocity of the workpiece can be calculated by Equation (3).

$$F = m\frac{dv}{dt} \rightarrow v_{final} = \frac{1}{m}\int_{0}^{²} F dt \qquad ...(3)$$

² is the time that the primary current lasts. The electromagnetic force exerted to the workpiece can be given as:

$$F = \iiint_{2} -j_{..} . B_r \hat{a}_z dv \qquad ...(4)$$

$_2$ denotes the volume of the workpiece. The magnetic density and the induced currents are a function of magnetic intensity, thus Equation (4) can be written as:

$$F = -«_0 \iint_{2} \left(H_r(z)\right)^2 \hat{a}_z dx.dy \qquad ...(5)$$

Taking into account Maxwell's equation, final velocity of the workpiece can be calculated as a function of the system parameters:

$$v_{final} = \frac{-«_0}{m}\int_{0}^{²} i^2(t)dt \left[\iint_{2} \left(\int_{1} \frac{\hat{a}_{..} \times \hat{a}_R}{4® R^2} dv \right)^2 \hat{a}_z dx.dy \right] \qquad ...(6)$$

$_1$ in integral boundaries denotes the volume of the coil. As it can be seen Equation (5) consists of two parts. First part indicates the energy transferred to the coil, and second part is a function of system geometrical parameters. Consequently, parameters that affect these two factors are capable of altering performance of the system.

Resistant of the primary system is the only parameter that affects the amount of the energy transferred to the coil,thus other electrical parameter such as the frequency of the applied current, initial voltage and capacitance of the capacitor bank, play no role on desired output of the system. Resistance of the circuit is the most important parameter which affects the efficiency of the system. Table 2 showsthe output of the system by variation of capacitance

Table 2: Output of the System in Different Frequencies

C[«F]	f[kHz]	V[kV]	¦	V[m/s]
112	7/4%	42840	42928	50
120	4/5%	92/8	42862	150
132	4/6%	42740	42770	450

of the capacitor bank at constant initial energy. It is obvious that itchanges the frequency of the applied current.

The displacement of the workpiece by varying the frequency at a constant energy is shown in Figure 2. As it can be seen the way that the workpiece accelerates, doesn't change by variation of the frequency.

Table 3 shows the outputs of the system for different resistances, the loss caused by resistance of the workpiece is also included.

The Thickness of Workpiece

During the current induction process, the electromagnetic field created by the current passing through the coil flowing on the surface of the workpiece, intends to diffuse from the regions with higher density of energy in vicinity of the coil to regions with lower ones. Despite their tendency to penetrate through the work-piece, these fields can't penetrate more than a specific depth, called *skin depth*. Skin depth of a given metal is dependent on conductivity, permeability and applied frequency as:

$$¢\,[m] = \sqrt{\frac{2}{\mu\,[rad/s] \pm [S/m] . « [Wb/A.m]}} \quad ...(7)$$

In this equation, µ is the angular frequency of the induced current, ± and « are conductivity and permeability of the moving contact. For the specific configuration considered here, the skin depth of the workpiece is about 1 mm (Gharghabi *et al*., 2011) studied the effect of various system parameters on tubular electro-magnetic forming. They predicted the behaviour of the workpiece under the test numerically and confirmed the results with experiments. It was shown that if the thickness of the workpiece is greater than its skin depth, the exerted force is always repulsive. On the other hand if thickness of the workpiece is smaller than its skin depth, the workpiece might experience attractive force at some intervals. They also, investigated the effect presence of a field-shaper and its impact on the system performance and efficiency. (Dordizadeh, 2011) utilized the same effect in calculate electro-magnetic force to the moving contact of a fast acting circuit breaker.

It could be concluded that in order to achieve better performance of an EMF system, a thickness at least equal to the skin depth of the workpiece is required. But this conclusion ignores one important fact and that is,

Figure 2: Displacement of Workpiece

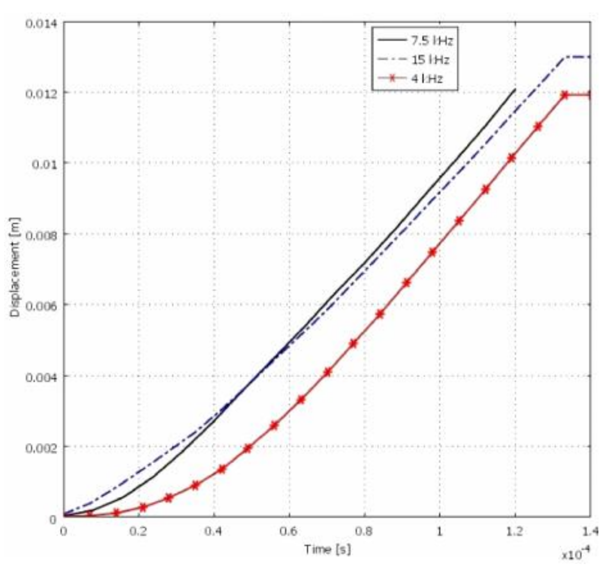


Table 3: Output of the System in Different Resistances

$R[\Omega]$	$V[m/s]$	η	$W_{res,Al}[J]$
0/03	141	5/7%	162
0/05	120	4/5%	145
0/08	98	6/3%	131
0/1	81	5/2%	119

increasing the thickness of the workpiece raises the mass and the mechanical strength of the workpiece, consequently reduces the efficiency and lowers the quality of the forming. Table 4 shows the result of the system for different thickness of the workpiece, in order tocompare two opposite effects of the thickness on performance of the system.

Table 2 illustrates that positive effect of decrease of the mass by reducing the thickness is more effective than negativeeffect resulted by decrease of average force exerted to the workpiece.

Several authors (Babaei *et al.*, 2013; Babaei *et al.*, 2014; Akhlaghi *et al.*, 2015; and Akhlaghi *et al.*, 2016) studied the influence of the electro-magnetic forces on the performance of the different components of electrical systems. The electromagnetic interference (EMI) noise caused by repulsion force generated from the interaction of the two magnetic fields can highly affect the nearby power devices in high-voltage applications (Mojab *et al.*, 2014). Moreover, to study the electromagnetic process accurately, the finite-element method is used which applies an exact analysis of magnetic materials (Jafarishyadeh *et al.*, 2016).

Gharghabi *et al.* (2016) studied the effect of the current impulse and the resultant highly

Table 4: Final Velocity for Different Thickness of Workpiece

Thickness [mm]	Mass [g]	Average Force [n]	Velocity [m/s]
0/1	1/52	1/24e+4	2506/5
1	15/24	2/035e+4	372/2
5	76/48	2/036e+4	74/6

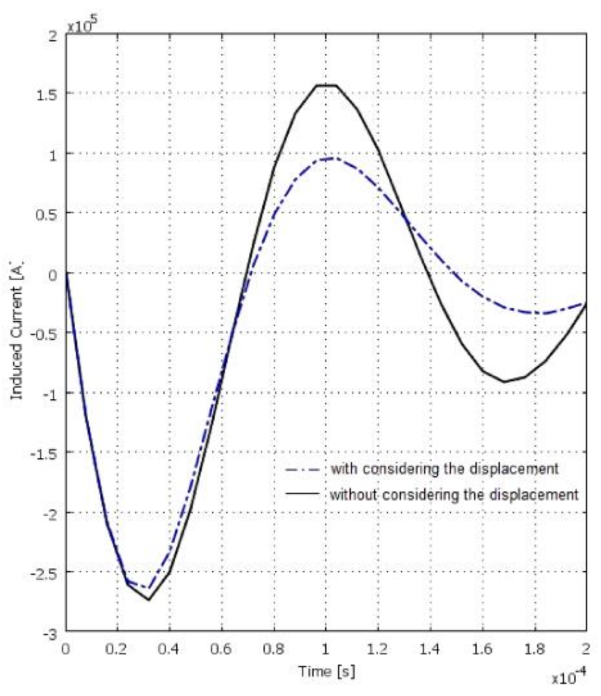
time varying electromagnetic field on the modern composite materials. They concluded that, flow of current impulse, even at lower magnitudes, could have irreversible impact on the material structure.

Equivalent Inductance

The displacement of the workpiece during applying the primary current affects the system equivalent inductance. Consequently parameters of the equivalent circuit vary with time. Since the displacement of contact upward causes reduction in magnitude of the induced currents, the magnetic field produced by eddy currents have less effect on attenuating the magnetic field produced by main current. Therefore the movement of the contact increases the system equivalent inductance.

Although the effect of the displacement of the workpiece on the primary current is

Figure 3: Inductance of the System



negligible and the variation of the primary current with or without considering the displacement of the workpiece is not significant, its effect cannot be entirely ignored. When the workpiece moves upward, while the applied current still exists, the magnetic pressure weakens which leads to decrease of induced currentsand the resultant force. It must be noted, since there is no displacement in the tubular EMF, this effect can be ignored. Figure 3 shows the surface integral of induced currents with and without considering the effect of the displacement of the workpiece.

Figure 3 demonstrates the fact that the effect of displacement of the workpiece is considerable and cannot be ignored. Because the difference of two form of simulation are significant and ignoring this phenomena could cause a notable error. The repulsive force could also be used in Voter machines (Karan and Chakroborty, 2016).

Relative Area of the Workpiece

The area of the workpiece facing the coil has two effects. First it determines the mass of the workpiece. As it was shown in Eq. final velocity ofthe workpiece is inversely proportional to its mass.

On the other hand, increasing the area of the workpiece until it covers the coil completely, causes increase of the produced magnetic pressure, and consequently raises the exerted force and final velocity. In order to compare these two opposing effect the results of performed simulations are shown in Table 5.

Table 5: Results for Different Radius of the Workpiece

***r*[*cm*]**	***m*[*g*]**	***L*[«*H*]**	***V*[*m/s*]**	¦
0/01 06	2/7	4/23	142	%0/5
0/02 12	11	3/97	184	%3/2
0/04 24	45	3/12	120	%5/4
0/08 28	90	3/04	40	%2/4

Table 5 indicates,when the area of the workpiece is smaller than the area of the coil, amplifying effect of the increase of the magnetic pressure play an important role. But when the area of the workpieceexceeds that of the coil, the attenuating effect of the mass is more considerable. Several authors have attempted (Khalili *et al.*, 2016) to model the complex feature of the workpiece movement using finite element methods.

CONCLUSION

In this paper, a full detailed result of simulation of a sheet metal forming has been given. Additionally, effect of different parameters in the final velocity has been studied. As a conclusion, following results can be inferred.

- Considering the skin depth parameter as an obligationin such a way that the thickness of the workpiece be greater than skin depth, can be disregarded. Because the effect of mass is greater than the effect of decrease of the average exerted force. As a result skin depth of the workpiece imposes no limitation on performance of a sheet metal forming systems.
- The frequency of the discharged current has two major influences: one is its impact on the amplitude of the produced force; the other is the duration that the primary current lasts.It was shown that the output of the system is independent of the frequency of the main current. And also the initial voltage and the capacitance of capacitor have no effect on performance of the system

individually. But their combination constitutes the initial energy of the system.

- The efficiency of the system is a function of the geometrical characteristics of the system and the amount of the energy transferred to the coil. The resistance of the system is the parameter that affects the amount of the energy transferred to the coil.
- The distance between the workpiece and the working coil and also the duration of the primary current must be in such a way that the primary currents and therefore the resultant force damps before the workpiece hits the die. It ensures that all the possible energy is transferred to the workpiece.

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