A Review on Electromagnetic Forming Process

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Abstract

Electromagnetic forming (EMF) is a non-contact forming technique. It is an impulse or high-velocity forming method using pulsed magnetic field by application of Lorentz’ forces to the work piece preferably made of highly electrically conductive material without having working medium and mechanical contact. Therefore, hollow profiles can be compressed or expanded as well as 2D or 3D sheet metal can be shaped, joined or cut. Electromagnetic forming process has very high strain rate and velocity in comparison to conventional process. Therefore, the Forming limits can be extended for several materials. In this paper, the state of the art of electromagnetic forming is reviewed subjected to following aspects - Research work on parameters related to acting load, Work piece deformation, Interaction between load parameters and work piece deformation, Behaviour of materials, Energy interaction during the process and Research regarding the principle and application of electromagnetic forming. On the basis of this study it is proposed why electromagnetic forming has not been widely initiated in industrial manufacturing processes up to now and how the challenges for its widespread applications can be meet.

Keywords: Electromagnetic forming ; high-speed forming ; impulse forming ; Finite element model ; Magnetic force ; Electromagnetic sheet forming ; Tube bulging ; Numerical simulation.

1. Introduction

Electromagnetic forming (EMF) is a high-speed forming method also called impulse forming process. During the EMF process, intense transient magnetic field produced around coil when the discharge current runs through it. According to electromagnetic induction law of Faraday, when the metallic object placed in magnetic field, eddy current will be produced. Two opposite direction of flowing current created a large magnitude magnetic repulsion force between the coil and the metal object (work piece) (see in fig1). This force is used to form work piece at very

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high speed Mamalis (2004), Corriea (2008). Maxwell (1873) described physical effects which is the basic of EMF principle. To deform solid conductors Kapitza (1924) generate sufficient magnetic field strengths. Thus he provided the foundation for the EMF process. This principle is technologically exploiting for a target-oriented forming of metals. Different applications and detail description is given by Brower(1969). By using electromagnetic forming tubular components or hollow profiles can compressed, expand (i.e. bulge), initially flat or three-dimensional sheet metals can be formed (see Fig.2). On the basis of these three different processes variants, types of coils for EMF can be distinguished. In the expansion, tubular work piece around the coil while in compression the coil encloses the work piece. Electromagnetic forming with direct electrode contact is a variant apart from these three major process variants. It is mentioned in Furth and Waniek (1962). Current flow in the work piece is induced by magnet in most cases. While Furth and Waniek (1962) claimed that method in which current directly passing through is more efficient than the conventional procedure. They introduced the idea of electromagnetic forming by pulling. While in the most of the applications the work piece is always pushed away from the tool. They suggest a special setup in order to establish pulling force. Another special variant is mentioned in Brower (1966) in which the elastic medium is used to apply electromagnetic force. He also established the set up for electromagnetic forming in which he used pressure concentrator and an elastomeric punch, which is placed between the tool coil and work piece. This process is not limited to electrically conductive material. A comparison between electromagnetic forming through an elastic medium and direct electromagnetic forming had given in Livshitz et. al. (2004). Only the electromagnetic compression has advantages compared to conventional forming processes at all. A kind of renaissance can be observed over the last years in electromagnetic forming, which is related to implementing lightweight construction concepts in the automotive industry. The electromagnetic sheet metal forming does not have that much significance with in industry but is expected to be increased. The electromagnetic forming process has many advantages in comparison to conventional forming processes. In EMF process the ductility of work piece increase significantly as compare to conventional forming process (Seth and Daehn, 2005), though the reason behind this increase in ductility is still being debated.
2. Principal of electromagnetic forming

The equivalent circuit diagram for the setup of electromagnetic forming is shown in fig-3. To form highly electrically conductive material a magnetic field is required, which is achieved by pulse generator. There were so many circuit diagrams of this setup given in literature but fig-3 is the most descriptive design of circuit. In this circuit capacitor C, inductance Li and resistor Ri are in the series, representing as a forming machine. The tool coil \( R_{\text{coil}} \) and its inductance \( L_{\text{coil}} \) both are connected to the pulse power generator in series (see Fig-3). The reduced version of this circuit is shown in Fig-4.

Capacitor battery stores the energy. The charging energy \( E_c \) of this capacitor battery is calculated from the charging voltage \( U(t) \) and the capacity C (see eq-1).

\[
E_c(t) = \frac{1}{2} CU(t)^2
\]  

Magnetic pressure acts only in areas of work piece close to coil. Therefore the deformation of work piece starts in these areas with velocity \( 10^2 \) m/s. The different directions of current, magnetic field lines, and magnetic pressure are shown in Fig-2. The setup is complimented by an additional component in tube compression process. This component is known as field shaper. In some publications it is called field concentrator. Firstly Babat and Losinsky
(1940) used field shaper to heat workpiece inductively. In comparison to direct acting coil, the mechanical loading of tool coil can be significantly reduced by using field shaper, resulting in a higher coil tool life (Kim and Platner, 1959). Combination of inductive heating and electromagnetic forming can be used. To produce a more uniform magnetic field and pressure for sheet metal forming Kamal and Daehn (2007) used a field shaper. During electromagnetic tube compression to support the workpiece a mandrel can be placed inside the workpiece.

3. Electromagnetic tube compression

Volume force can be determined on the basis of the Magnetic flux density $\bar{B}$ and the current density $\bar{J}$ (see eq-2). The flux density is the result of product of the magnetic field strength $H$ and permeability $\mu$. The negative derivative of magnetic field strength $H$ with respect to the radius $r$ is equal to current density $J$ (see eq-3). The radial forces acting on a tubular workpiece $F_r$ can be calculated using eq-4. These volume forces can be transformed to virtual surface forces mathematically. It is called pressure $P$. The pressure difference between two points on workpiece can be calculated by integrating acting force, using inner radius $r_1$ and outer radius $r_2$ as integration limits (see eq-5).

$$\vec{F} = \vec{j} \times \vec{B}$$

$$\vec{J} = -\frac{\partial H}{\partial r}$$

$$F_r = -\mu H \frac{\partial H}{\partial r} = -\frac{1}{2} \frac{\partial (H^2)}{\partial r}$$

$$P(r, t) = \int_{r_1}^{r_2} F(r, t) dr = \frac{1}{2} \mu [H_{gap}^2(t) - H_{pen}^2(t)]$$

In both tube and sheet forming process the magnetic pressure depends only on the penetrated magnetic field $H_{pen}$ and on the strength of magnetic field in the gap between workpiece and the tool coil $H_{gap}$. Using suitable measuring loops these field strengths can be measured in tube compression process. The axial distribution of the field strength in the gap $H_{gap}$ for a direct acting compression coil setup can be calculated. For this a relationship based on the coil length $l$, effective gap $a$, the coil current $I(t)$ and the number of turns of the tool coil $n$ is required. It is called distribution coefficient $K_H$ (see eq-7).

$$H_{gap}(t) = \frac{nI(t)}{l} K_H$$

$$K_H = \frac{1}{\pi} \left( \arctan \frac{2x+1}{a} - \arctan \frac{2x-1}{a} \right)$$

$$a = a_{Air} + \frac{1}{2} (\delta_{WP} + \delta_{coil})$$

Here $a$ is the effective gap, $a_{Air}$ is the width of the air gap and $\delta_{WP}$ is the skin depth of the workpiece and $\delta_{coil}$ is the skin depth of the coil. In order to analyse the effect of field shaper having trapezoidal cross-section on the pressure distribution Yu et al. (2005) used two dimensional FE simulations. Finally a 3dimensional FE simulation was presented by Bahmani (2008). During the first half wave of the coil current, the deformation process completes with the first pressure pulse. Rajive (2012) had simulated the electromagnetic compression forming, carried out on steel tubes of 2.3mm wall thickness and 76.2mm outer diameter. They had compared the experimental values of electromagnetic formed tubes available in literature with results of simulation. Haiping (2009) investigated the tendency of homogeneous radial deformation during electromagnetic compression of aluminium tube through sequential coupling numerical simulation and experiments. They found that the tendency depends on the length ratio of tube to coil ($R$). The discharge length, corresponding to the homogeneous radial deformation is insensitive to discharge voltage. $R$ has critical value $R_c$. The value of $R_c$ can be zero or 1 and it can be increased with the coil length also. They concluded that when- 1) $R > R_c$, the final tube presents horn shape. 2) $R < R_c$, the final tube presents drum shape.

4. Electromagnetic tube expansion

In the electromagnetic forming process the field strength in the gap depends on the current induced in the work
piece. This induced current in tube expansion process is not as high as the coil current. Therefore, the magnetic strength cannot be calculated from the coil current. In order to determine the force acting on the work piece, the magnetic field between the tool coil and work piece is measured. To determine the acting loads on the basis of the measured current in the work piece and measured coil current, Gourdin (1989) used principle of virtual work. In expansion process the geometric stiffness decreases while in compression process stiffness increase over the process time. The influence of inertia forces is higher in case of lower stiffness. Thomas (2009) introduced a full coupled Lagrangian least action variation principle considering magnetic flux, electric potentials and the displacement field as independent variable. This variation principle provides an efficient staggered solution algorithm, combining with the vibration integration numerical scheme. Zhong (2007) had employed finite code ANSYS for the simulation of the electromagnetic tube bulging process. To obtain the radial and axial magnetic pressure acting on the tube ANSYS/EMAG was used. The time space distribution of magnetic pressure was presented on various tube lengths. Effect of tube size on the high velocity deformation, distribution of radial magnetic pressure and axial magnetic pressure were discussed. The axial magnetic pressure of various sizes of tube found to be zero at the centre, greater at the end points (when the tube length is smaller or equal to the coil length), greater at the location equal to the coil length and decreased to the adjacent region (when the tube length is bigger than the coil length). They found that the deformation along the length and radial magnetic pressure distribution changes with dimensionless tube length. Thomas (2007) had applied the concept of forming limit diagrams (FLDs) to study the ductility of freely expanding electromagnetically loaded aluminium tubes. Necking strains of various tubes geometries were measured which were loaded by different coils and currents. They plotted experimental results in principle strain space show reasonable agreement with the corresponding theoretical FLD predictions. It was indicated that forming limits increase 2- to 3-fold with respect to the quasi static case. In this paper the quantitative comparison carried out between theoretical calculations for the onset of necking in sheet and the results, obtained from the free expansion of electromagnetically loaded aluminium alloy tubes.

5. Electromagnetic sheet metal forming

The negative derivative of magnetic field strength H with respect to the z- coordinate is equal to current density \( \mathbf{J} \) (see eq-9). In electromagnetic sheet metal forming, force acting on a sheet metal work piece can be calculated by eq-10. The magnetic pressure can be calculated by integrating the acting force over the distance.

\[
\mathbf{J} = -\frac{\partial H}{\partial z}
\]

\[
F_z = -\mu H \frac{\partial H}{\partial z} - \frac{1}{2} \mu \frac{\partial (H^2)}{\partial z}
\]  

(9)  

(10)

In an electromagnetic sheet metal forming process there are few papers mentioning magnetic pressure as compare to tube compression because forming of sheet metal is the most complex process variant. During deformation increase of the gap volume between the work piece and tool coil influence the acting magnetic pressure, this effect is much more relevant in case of sheet metal forming than the tube compression or expansion. Therefore the mathematical description of the process in close form is not possible. Equation had given regarding the magnetic pressure \( P_r \) and the magnetic field \( H_r \) in the radial direction. A harmonic field simulation is used to determine the pressure distribution. The ratio of the field strength \( H_{gap}(t_{max}, r) \) (when the current reaches the maximum) to the maximum possible field strength \( H_o(t_{max}) \) is known as factor of pressure distribution \( K_H(r) \), analogous to the coefficient for the tube compression (see eq-8).

\[
K_H(r) = \frac{H_{gap}(t_{max}, r)}{H_o(t_{max})} \quad \text{With} \quad H_o = \frac{n l(t_{max})}{l_{coil}}
\]

(11)

During sheet metal deformation process an increase of gap volume decreases the magnetic field Strength therefore a continuously decreasing pressure can be observed. After some deformation of work piece pressure decreases to a negligible level in this situation only inertia force drives the process. Correia (2008) studied the effect of electromagnetic and mechanical forces, produced during sheet metal forming process. Problem was analyzed in ABAQUS/Explicit. They discussed the electromagnetic forming in two ways, first one deals with the formulation
and computation of electromagnetic parameters and the second one deals with a FES. They calculated the parameters such as Electromagnetic field density, electromagnetic force distribution and coil discharge by developing the numerical and analytical tool. Unger (2008) formulated a thermo-magneto-mechanical multifield model and used to simulate electromagnetic sheet metal forming processes (EMF) based on Lorentz force principle. After simulation carried on a sheet metal made of aluminum alloy AA6005, the deformation results of the sheet metal are obtained. Wei (2009) studied Effect of temperature on plastic deformation of sheet by electromagnetic force. They used a new method of controlling welding distortion with trailing electromagnetic force. They studied the plastic deformation of sheet using electromagnetic force at different temperature. It was simulated by ANSYS. They employed Physical environment method to study the electromagnetic force acting on sheet in the presence of high temperature and deformation of sheet. They concluded following results: (1) The magnitude of peak axial force decreases with increasing temperature, on the other hand the magnitude of peak radial force increases with increasing temperature. The variation of peak electromagnetic force with temperature is nonlinear. (2) When temperature increases electromagnetic force decreases due to decrease of yield strength. (3) They proposed that, the electromagnetic force is employed to control welding stain during welding.

Chu (2012) had proposed a new method and implemented it to determine the flow curve of aluminum alloy 1100-O at high strain rates. By combining retrieved effective stress from simulation and measured effective strain from deformed work piece. The accuracy of determining flow curve is increased by iteration procedure. They had simulated forming process by using determined flow curves. They observed that the deviation in strain could be reduced from 17.9% to 6.74% and effective strain of 0.56 could be achieved by deforming material without failure. Xiao-hui (2011) had analyzed the distribution of magnetic forces and current on sheet and coil. They proposed reason for coil failure. To analyze the deformation law of the sheet they had given the magnetic forces on the sheet as input into software ANSYS/LS-DYNA. They concluded that by increasing distance between the coil and the sheet, the distribution of magnetic forces on the uniform pressure electromagnetic actuator is changed which may cause coil failure. Okoye (2006) applied a hybrid forming process for the formation of metals based on Lorentz force termed as EMAS (Electromagnetic-assisted stamping). This technology was applied under consideration of making fuel efficient cars and aircrafts, large size vehicles panels, and improved formability limit of materials. They gave more attention on designing of coil such as pressure distribution across the coil. The coils were finally configured to bend in order to form shapes, single, double or more curved. The design was optimized subjected to maximum electrical efficiency to increase the durability of the coil.

6. Energy interaction during electromagnetic forming

In electromagnetic forming process initially the energy stored in the pulsed power generator as capacitive energy. This energy is used to deform the work piece at the end.

Fig.5. Energy transfer during electromagnetic forming.
A complex energy transfer is there in between these two stages. Only parts of stored energy transfer to the coil and used to deform work piece. There are losses in between energy storage and deformation of work piece (see Fig-05). They mentioned the range of efficiency of electromagnetic forming 10% to 40%. Psyk (2007, 2011) was focused on the effect of energy transfer on the forming results. The Capacitor charging energy $E_c$ at first is transferred into a magnetic pressure pulse $p$. This magnetic pressure pulse is transferred into kinetic energy $E_{kin}$ and then transferred into forming energy $E_{def}$. During deformation process there is a moment when pressure has decreased to zero, the kinetic energy stored in the work piece is used to finish the forming process. He performed two exemplary forming tasks. In first task a die with a spherical cavity used to form an aluminium sheet and in the second task a conical die is used to form aluminium sheet. The total efficiency of process found to be 23% in first task and 28% in second task.

Conclusions

1] This review shows that most of the papers are limited to explain the electromagnetic forming process principle, showing process advantages and its high expectations.

2] It is noticed that products with small to large lot size can be formed using EMF. High production rate can be easily achieved.

3] It is very difficult to estimate the feasibility of manufacturing task which is performed by electromagnetic forming, joining or cutting because of unavailability of software packages (Tools). For the modelling of EMF processes, there is a lack of user-friendly commercial finite-element-software. The existing tools are limited to 2D or simple 3D models; they cannot handle the complex industrial task. Very few of them which might be suitable for these complex tasks require extremely long time for calculations.

4] Quantitative simulation of EMF requires accurate data obtained considering the specific load case (i.e. high strain rate). Currently in many cases material data obtained from conventional quasi static test is used, which is only suitable for qualitative simulation.

5] Very less research works considering tool design as well as coil lifetime have been published. Specific guidelines are required for the load oriented coil design.

6] The Fastest growth in use of EMF technology is recorded in the late 1990s because of implementation of light weight construction concept. It is realized that the work piece properties achieved by EMF process cannot be achieved by other methods.

References


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