51. IWK

Internationales Wissenschaftliches Kolloquium
International Scientific Colloquium

PROCEEDINGS **11-15 September 2006**

FACULTY OF ELECTRICAL ENGINEERING AND INFORMATION SCIENCE

INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING - DEVICES AND SYSTEMS, MATERIALS AND TECHNOLOGIES FOR THE FUTURE

Startseite / Index:
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TECHNISCHE UNIVERSITÄT
ILMENAU

Impressum

Herausgeber: Der Rektor der Technischen Universität Ilmenau
Univ.-Prof. Dr. rer. nat. habil. Peter Scharff

Redaktion: Referat Marketing und Studentische Angelegenheiten
Andrea Schneider

Fakultät für Elektrotechnik und Informationstechnik
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Redaktionsschluss: 07. Juli 2006

Technische Realisierung (CD-Rom-Ausgabe):
Institut für Medientechnik an der TU Ilmenau
Dipl.-Ing. Christian Weigel
Dipl.-Ing. Marco Albrecht
Dipl.-Ing. Helge Drumm

Technische Realisierung (Online-Ausgabe):
Universitätsbibliothek Ilmenau
ilmedia
Postfach 10 05 65
98684 Ilmenau

Verlag: isle
Verlag ISLE, Betriebsstätte des ISLE e.V.
Werner-von-Siemens-Str. 16
98693 Ilrnenau

ISBN (Druckausgabe): 3-938843-15-2
ISBN (CD-Rom-Ausgabe): 3-938843-16-0

Startseite / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=12391

51st Internationales Wissenschaftliches Kolloquium
Technische Universität Ilmenau
September 11 – 15, 2006

K. Niayesh, A. Karimi

Application of Field-shapers to localize applied forces during Impulse Electromagnetic Forming Process

ELECTRO-PROCESSING TECHNOLOGIES

Abstract

Impulse Electromagnetic Forming (IEMF) is an effective and powerful technique widely used for joining and shaping metals .The electromagnetic forming technique has been in use commercially for the last 30 years. Higher precision, rapidity and other several advantages in comparison with the other techniques of high velocity forming make this technique to be the only high velocity forming method to gain significant acceptance in commercial metal working. In this technique, a metal work-piece is pushed to a die and formed by a pressure created using an intensive, transient magnetic field. This magnetic field is produced by passing a pulse of electric current through a forming coil in a pulsed power circuit. The produced transient magnetic field induces eddy currents in the surface of workpiece. Induced eddy currents in workpiece produce a magnetic field with reverse direction of initial magnetic field cause to a mutual repulsion between coil and workpiece result to throwing the workpiece toward the die.

In this process created magnetic forces applied to workpiece are much like uniform, but in real applications, some regions of a workpiece have to be more deformed and therefore a much greater pressure has to be applied to these regions. The task of concentration of magnetic forces to some desired regions can be accomplished using field-shapers. In this paper, using a multi-physics simulation tool the transient process of electromagnetic forming is simulated and some simple guidelines to design the field-shaper have been derived. The results indicate that application of proper designed field-shaper can result in an increase of magnetic pressure in the desired regions of several orders of magnitude.

Introduction

High-rate forming processes, such as impulsed electromagnetic (IEMF) forming, can promote significant increases in strain to failure in low ductility materials due to strain rate and inertial stabilization of material failure modes [1]. Impulsed Electromagnetic forming (IEMF) is a powerful and effective technique of high-rate forming. It can be considered as one of the best high-rate forming methods from the several aspects such as high cleanness, cost-efficiency and productivity. Applying this technique, it is also possible to improve the formability of some materials such as aluminum that is a good candidate material for use in automotive industrial and many other applications. This makes it possible to avoid undesirable forming of conventional quasi-static methods like wrinkling, tearing, springback and any unexpected effects on the metal workpiece [1, 2].

A main part of IEMF system is Field shaper that concentrates the magnetic field in desired points of a metal workpiece in forming process. i.e. A field-shaper transmit the energy produced by inductor system to the expected points .It‘s clear that any where we transmit the energy, there is some energy dissipation in transmitter cause to decrease the efficiency of the system, therefore applying of a field-shaper decrease the efficiency of an IEMF system but using this part. The same IEMF setup can be applied for several types of forming and there is no need to replace the coil system for modifying the magnetic field for a special case. It is only enough to replace the field-shaper with another one with modified design [3]. In spite of the important role of the field-shaper in electromagnetic forming process, there is little coverage in the literature. In this paper, electromagnetic field simulations are carried out for an IEMF system with a cylindrical structure used for compression of a tube implied in reference [3]. These simulations are done using a commercial software package (Maxwell) in the IEMF Systems with and without field-shaper. In the last part of the paper, influence of the insertion of a field-shaper on the magnetic flux density distribution is discussed and some considerations in designing of field shaper for enhancing the magnetic pressure in expected points are proposed.

The main structure of an IEMF system

An IEMF system is capable to be applied for many reasons such as compression or expansion metal tubes, forming flat sheets (such as panels in automotive industries), welding and many other applications. However the main principle in all of the applications of this technique is the same. In this paper before focusing on field-shaper, it's preferred to describe about an IEMF system construction in compression of a tube. An IEMF system consists of some main parts shown in figure (1) as follows:

1 - Capacitor bank for storing the electrical energy

2 - Fast switch for connecting capacitor banks to Work coils and interrupting it

3 -Work coil for creating magnetic field in the
Work zone

4- Workpiece

5-Die or matrix (is shown its cross-section in the lower part of figure (2)).

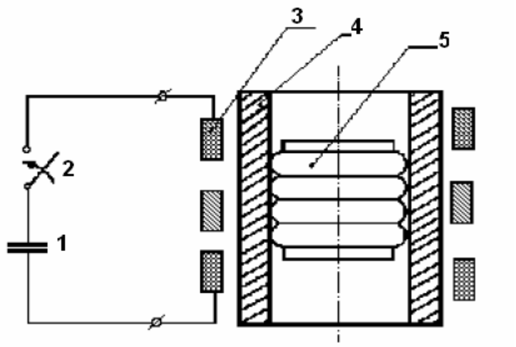


Figure 1: The main structure of an IEMF system

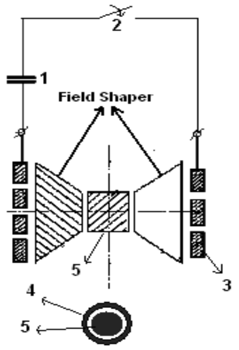


Figure 2: An IEMF system applied With a field-shaper (compression)

In general, an IEMF consists of a pulse current generating circuit, work coil, workpiece and matrix. It is illustrated an IEMF with a field-shaper in figure 2. Other parts such as controlled commutator are also added as minor utilities for increasing the rate of production and more productivity [3].

Physical description of an IEMF process

In this process, the electrical energy stored in capacitor bank, discharges in the workcoil while the switch closes cause to flow a pulsed current with significant magnitude (about several tens to hundreds kilo amperes) and high frequency (normally between 10 to 100 kilo hertz).This current produces an intensive and transient magnetic field around the workcoil. With consideration of the faraday law in relation (1), when a metal piece is located in exposure to the magnetic field, eddy currents are induced in workpiece surface in the reverse direction of the initial current injected in workcoil.

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad (1)$$

Therefore, there are two conductors in vicinity of together with reverse direction currents (fixed work coil and free workpiece) consequently the workcoil repels the workpiece and throws it to the die (matrix). Although in the majority of applications of IEMF technique, workcoil doesn't exert the magnetic pressure on workpiece directly and this role is executed by the field shaper located between the workcoil and workpiece [3]. In this case, for acquiring the equations for the exerted pressure on workpiece surface and analyzing it, we consider a cylindrical structure IEMF system for compression the tubes in figure 2 from the reference [3]. This system is a symmetrical geometry, for simplifying the problem, so that it can be considered as a two-dimensional problem as shown in figure 3.

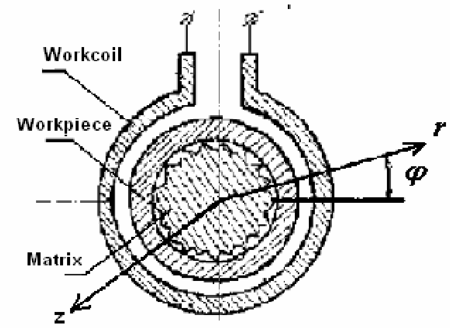


Figure 2: A cylindrical IEMF structure system for compression

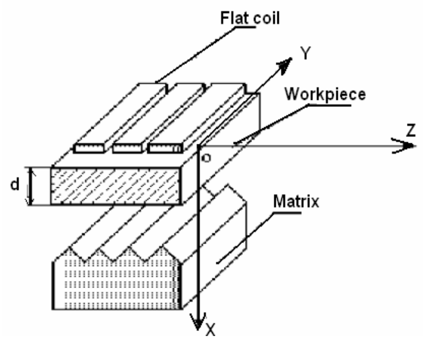


Figure 3: An IEMF system with flat structure

The system is considered long enough in Y axis direction and the current exerted in workcoil is flowing in direction of Y axis. Applying the ampere law (equation 2), it can be seen that the current in workcoil produces a magnetic field in direction of z axis.

$$\vec{J}_y = \nabla \times \vec{H} = -\frac{d\vec{H}_z(x)}{dt} \cdot a_y \qquad (2)$$

The induced electric field produces an eddy current in workpiece with the reverse direction of the initial current flowing through workcoil and the magnitude of this current is related to the conductivity of workpiece as follows:

$$J_{eddy} = \sigma \cdot E \qquad (3)$$

Consequently the flowing of eddy currents on the surface of the workpiece leads to a force application on the surface of workpiece in agreement with equation 4.

$$\overrightarrow{f_x}(x) = \overrightarrow{J}_y \times \overrightarrow{H}_z(x) \qquad (4)$$

The direction of this force is in the reverse line of X axis. Finally the exerted pressure is resulted from the relation (5)

$$p = \frac{\mu_0}{2}\int_0^d f_r(r).dr \quad = \quad -\frac{\mu_0}{2}\int_0^d \frac{d\,H_z(r)}{dt}\cdot H_z(r)\cdot dr$$

$$\Rightarrow \quad p = \frac{\mu_0}{2}\cdot(H_1^{\ 2} - H_2^{\ 2}) \qquad (5)$$

$$H_1 = H_z(0) \quad , \quad H_2 = H_z(d) \qquad (6)$$

Where *d* is the thickness of workpiece as shown in figure(3), H1 and H2 are the magnetic fields intensities on the boundary surfaces of the workpiece respectively one of the workpiece surfaces in the vicinity of the workcoil (x=0) and, another one is located near the Matrix(x=d).The relation (5) an (6), imply that the intensity of exerted pressure on workpiece surface in vicinity of the coil is related to difference between the squares of the tangent components of the magnetic intensities on the boundary surfaces of the workpiece and during an IEMF process. Therefore with decreasing the value of H2, the pressure on the surface of workpiece increases. On the other hand, EM waves intends to pass through the workpiece to the cavity located between the matrix and workpiece and push the workpiece toward the region with the lower density of energy. But the eddy currents flowing on its surface produce the EM field in the reverse direction of initial ones. The penetration depth can be easily expressed as:

$$\delta = \sqrt{\frac{1}{\pi\cdot\sigma\cdot\mu\cdot f}} \qquad (7)$$

It‘s obvious the less EM field penetrates on the workpiece surface, the more it exerts effective pressure on it. It must be noted that the penetration depth is much less than the thickness of workpiece and the intensity value of H2 in this condition is equal to zero leads to exerting maximum pressure on workpiece surface as given in equation 8:

$$p = \frac{\mu_0}{2}\cdot H_1^{\ 2} \qquad (8)$$

Although, there is a situation that the thickness of workpiece is less than the penetration depth causes to EM waves pass through the workpiece results to increase the value of H2 such as thin-walled workpiece. After it the EM pressure falls down finally it creates no pressure.

Designing and Simulation

After describing the IEMF process in general, in this part more attention is paid to the role of field-shaper in an IEMF process. For this purpose, an IEMF system applied for forming of metal sheets considered with and without field-shaper (see figures 4 and 5).

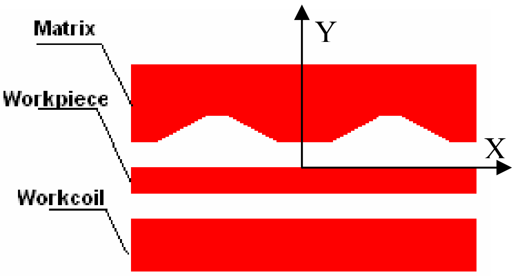


Figure (4): An IEMF system for forming metal sheet without using field-shaper

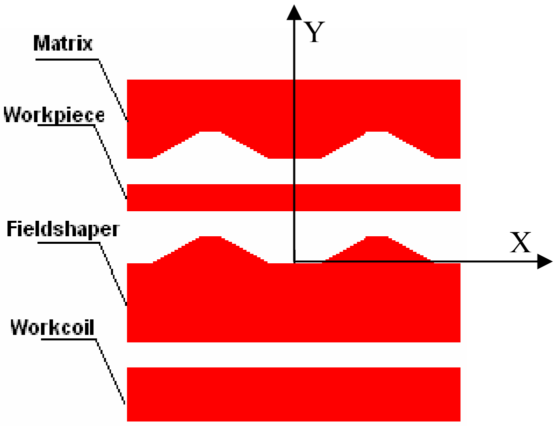


Figure (5): An IEMF system for forming metal sheet with applying field-shaper

For modeling this process, as stated earlier, a two dimensional simulation has been carried out. The current flowing through the workcoil (perpendicular to the page in z direction) has been assumed to have the magnitude and frequency of 10e6 Ampere and 30 kilohertz, respectively. To model the eddy current induced in all surface of the field-shaper, in accordance with the reference [5], an impedance boundary condition for the magnetic field in the vicinity of the surface od the workspiece combined with a current source of zero amplitude in the z direction are used.

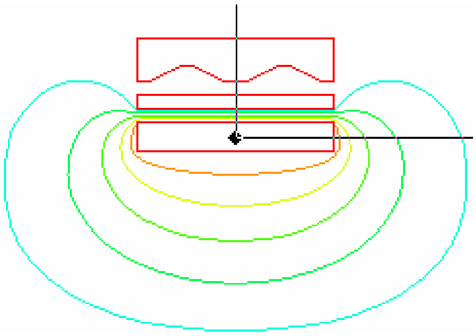


figure (6) : the profile of magnetic flux line in an IEMF system without field-shaper

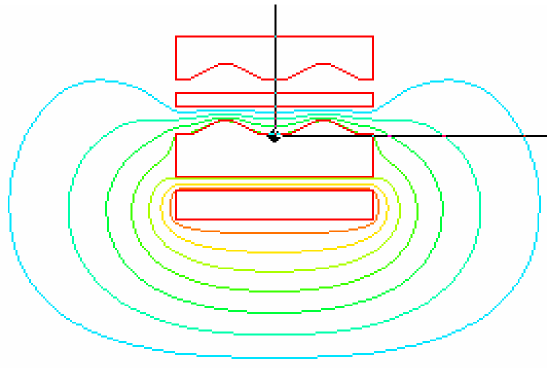


figure (7) : the profile of magnetic flux lines field in IEMF system with field-

The Magnetic flux lines of two IEMF systems related to figure 4 and 5 is illustrated in figure 6 and 7, respectively. Comparing the flux lines shown in figures 6 and 7, it can be seen that in the case with field-shaper, the magnetic flux lines are compressed at those points, where more pressure is required.

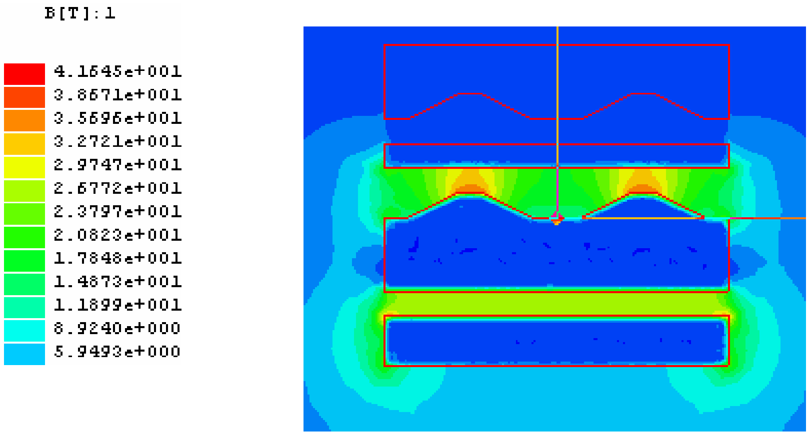
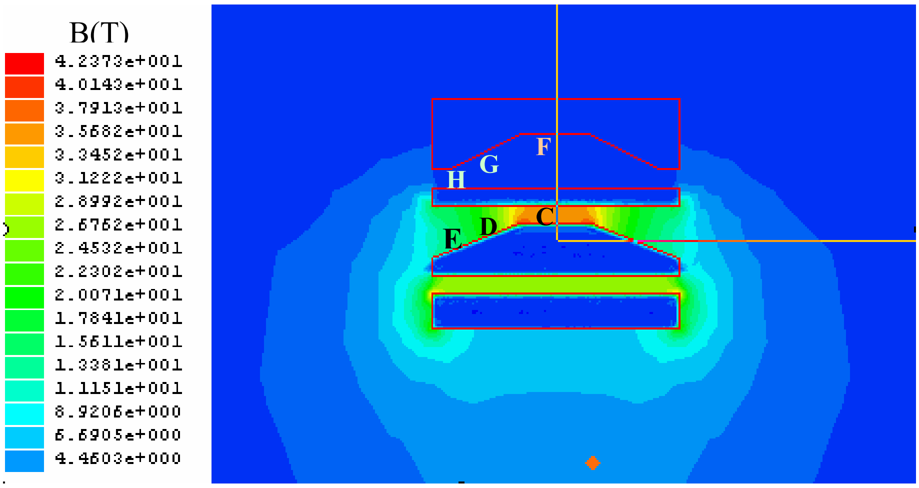


Figure (8): the flux density of magnetic field in the IEMF system

In the case without field-shaper, the density of flux lines is the same in the entire space between the coil and workpiece leading to exertion of a homogeneous pressure on the workpiece surface. But, in contrary, in case with field-shaper much higher magnetic flux densities on the top of two nodules can be achieved (see figure 8).



In figure 9, the distribution of the magnetic flux density (B) is shown for another matrix geometry. As it can be seen, the B in the “region E”, approximately has the value in the range of 8.92 to 17.8 Tesla and it increases gradually in a continuous spectrum to the range of 17.8 to 31.2 tesla in the “region D” and ultimately it reaches the value of 36 tesla in the top of the field-shaper in region of C. The variation of B on the surface of field-shaper in regions C is proportional to the depth of the matrix. By designing the field-shaper, It has to be taken into consideration that the field-shaper has the enough mechanical strength to stand the exerted pressure from the workcoil on its surface, therefore, besides the maximizing the magnetic flux density at the top region of field-shaper, mechanical issues have also be taken in consideration in selecting the geometry and material of the field-shaper.

Conclusion

IEMF technique is one of the most superior methods for forming and joining for several materials. There are some challenges and limitations to prevent applying this technique in some cases, e.g. maximum pressure and the right pressure distribution on the surface of the workpiece. Another challenge in this technique is the accurate modeling of the induced eddy currents, which plays a very important role in this process.

In this paper, applying the electromagnetic field simulations, the influence of insertion of field-shapers in impulsed electromagnetic forming systems is investigated. To model the induced eddy currents, an accurate model based on application of an impedance boundary condition in the vicinity of surface of the workpiece is used. The simulation results indicate that a manifold increase in the magnetic flux density at the points, where more pressure is required, can be achieved using field-shapers.

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