An Application of High-Power Electromagnetic Pulse: Forming of sheet metal using electromagnetic waves

Gokhan Inanan[1], Besim Baranoglu[2], Elif Aydin[1]

[1] Dept. of Electrical & Electronics Engng., Atilim University
kartal.gok@hotmail.com, elif.aydin@atilim.edu.tr
[2] Dept. of Manufacturing Engng., Atilim University
besim.baranoglu@atilim.edu.tr

Abstract

In this study, the application of high velocity metal forming process by means of electromagnetic field is proposed. Electromagnetic Sheet Metal Forming (ESMF) is a process of forming sheet metal with very high speed (in milliseconds) without mechanical contact using the energy density of a pulsed magnetic field. In this process, deformation of the workpiece is driven by a transient electric current that is induced in a coil using a capacitor bank and discharge switch. This study presents some experiments and their results by examining the effects of different parameters in the proposed ESMF setup. The analysis and modelling of Electromagnetic sheet metal forming (ESMF) process is presented, as well. It has been seen that, it is possible to design a new system using the outcomes of this study.

1. Introduction

In recent years, there has been high demand and increasing interest for the high velocity forming techniques such as electromagnetic forming. Significant increases in strain to failure in low ductility materials can be provided by high rate forming processes [1, 2]. Electromagnetic forming is a high speed process and it needs only a few milliseconds to form metal parts with using a pulsed magnetic field. In parallel with the configuration of the coil geometry, the method can be used for tube compression and tube expansion as well as for the forming of flat sheet metals. Sheet metal forming is one of the most valuable application areas of electromagnetic forming. Especially, aluminum alloy sheet is a candidate material for use in heavy vehicle, aviation and aerospace industries. Other sheet metal forming processes like deep drawing, punching, blanking and bending require complex and custom designed expensive devices [3].

Analysis of the Electromagnetic sheet metal forming (ESMF) is a very complex process and several recent studies propose numerical procedure explain working principles of this process. In order to investigate ESMF, Finite Element Method, Finite Difference Method or a model based on the law of Biot-Savart are employed [4–8].

In this study, the working principles of the electromagnetic forming system are studied in detail. The analysis and modelling of ESMF process is presented, as well. In order to design more advanced ESMF systems, theoretical and numerical modelling of the electromagnetic forming process is determined in this paper. Also, some experiments are made and the results are compared. The system in this study consists of a DC voltage source, a pulse capacitor bank, an actuator coil and a switch mechanism. The workpiece is held between two insulated blankholders and bulged with the application of the electromagnetic waves.

This work was supported by Atilim University under Grant No. ATU-BAP-A-1213-03.

2. Electromagnetic Forming Process

ESMF is a process to form the sheet metal in very high strain rates (the whole ESMF action completes in milliseconds) without mechanical contact using the energy density of a pulsed magnetic field [9]. Deformation of the workpiece is driven by the interaction of a current generated in the workpiece with a magnetic field generated by a coil adjacent to the workpiece [9].

The ESMF system consists of an R-L-C circuit (Figure-1) and the process starts when a capacitor bank is suddenly discharged through an actuator coil. The transient electric current that is flowing through the actuator coil generates a time-varying magnetic field and this magnetic field induces electric currents in nearby conductor. These induced currents are called as eddy currents and are created on the workpiece surface. These eddy currents have different flow directions in contrast to the ones in the coil. Therefore, a repulsive force is generated between the coil and the workpiece. If this force is enough to form the metal then it is formed according to the die. The first studies in the field of electromagnetic forming started with Harwey and Brower [9]. Brower later gives several application examples with important details [10].

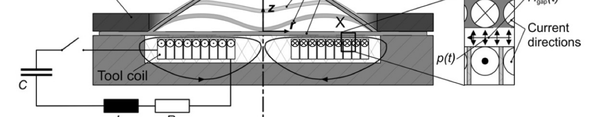

Figure 1. Schematic drawing of the electromagnetic sheet metal forming process [11]

In applying the electromagnetic forming to sheet metals, flat coils are used. In literature workpieces with thicknesses less than 5mm are successfully formed. Since the charged energy is based on the area to be formed, to form workpieces with larger areas, it is necessary to charge more energy in capacitors.

Considering other sheet metal forming processes, the effectiveness and efficiency in ESMF is relatively high. This is mainly due to the production rates supplied by the high forming velocities. The forming takes very little time, the limit in production rate is due to the feeding and handling of the sheet metal to the forming medium. If sufficiently fast equipment is provided, the output production rate is reported to be 3600 parts/piece [3].

Besides all these advantages, there are some disadvantages of the ESMF stated in related literature: Firstly, the effectiveness of the method depends on the electrical conductivity of the workpiece (the more the electrical conductivity, the more EM formability). Most suitable material is reported to be aluminum or annealed copper [1].

Also, the reported life for the coil is too short, that results in shorter times for tool replacement requirements. Also, due to the nature of the electromagnetic waves, not all of the produced energy is used in forming the material â the method is therefore energy-ineffective [1].

2.1. Circuit equations of ESMF

A high energy system that can discharge in a short time (a few microseconds) is needed for electromagnetic forming process. This system is represented by a serial circuit consisting of a high voltage capacitor bank , an inductance and a resistor should be selected to operate in the over damped condition. Basically, ESMF circuit can be analysed as a RLC circuit. The current flowing through the coil can be given by

$$i(t) = -\frac{V_C}{\omega_d L} e^{-\alpha t} \sin(\omega_d t) \tag{1}$$

where V_C is the initial voltage of the capacitor bank, ω_d and α are the neper frequency (or attenuation) and the modified frequency respectively:

$$\alpha = \frac{R}{2L} \; ; \; \omega_0 = \frac{1}{\sqrt{LC}} \; ; \; \zeta = \frac{\alpha}{\omega_0} \; ; \; \omega_d^2 = \omega_0^2(1-\zeta) \tag{2}$$

The energy stored in the capacitor bank is suddenly discharged by closing the high current switch between the charged capacitor and the inductor. The resulting current (Eq.1) which is a highly damped sinusoidal oscillation, is generated by the high energy system. According to the Faradayâs Law, this current generates an electromagnetic field by means of coil that creates eddy current which depend upon the material properties (conductive and permeability) and flow in the opposite direction in the workpiece. Electromagnetic equations can be derived from Maxwell's equations as:

$$\vec{\nabla} \times \vec{H} = \vec{J} \tag{3}$$

where $\vec{J}$ is the current density and $\vec{H}$ is the magnetic field. According to the electromagnetic equations, a current is induced on the workpiece due to the electromagnetic field caused by the high frequency current on the coil. The magnetic flux density can be given as

$$\vec{B} = \vec{\nabla} \times \vec{A} \tag{4}$$

where $\vec{B} = \mu\vec{H}$ is the magnetic flux density and $\vec{A}$ is the magnetic vector potential. The induced current due to the flux density flows in reverse direction to the coil current according to Lenz's law. The induced current generates Lorentz force on the workpiece which may be expressed as:

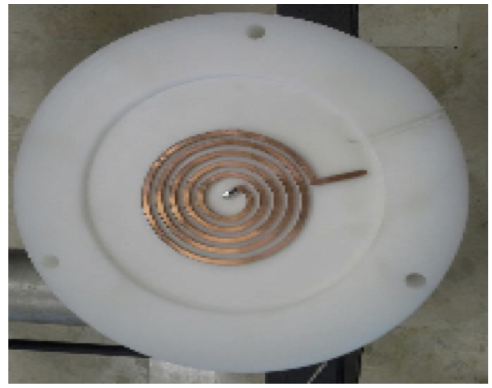

Figure 2. An example spiral coil used in this study

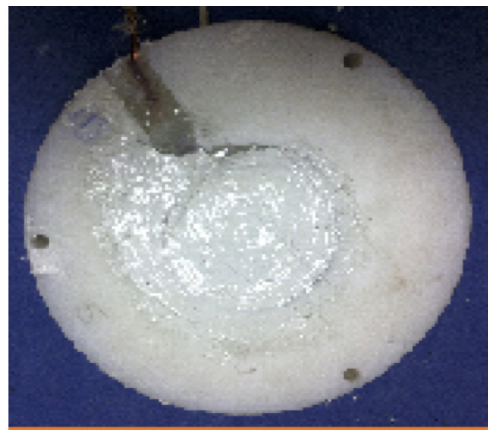

Figure 3. An example spiral coil used in this study embedded in refractory material

$$\vec{F} = \vec{J} \times \vec{B} \tag{5}$$

where $\vec{F}$ is the generated force that performs the forming action.

2.2. Design of Coils

The design of a proper coil is one of the most important issues in electromagnetic sheet metal forming system. Since the coil is the main element in the system that would provide the desired magnetic field (leading to the magnetic pressure [1]), in designing the coil, the strength as well as the capacity to transmit high current is important. Also, depending on the capacitance of the system, the inductance value is important together with its internal resistance, noting that a spiral coil with more turns (which would increase its inductance) would have a longer wire, which, in turn, increases the electrical resistance of the coil.

Besides electrical characteristics of the coil, the designs of geometrical properties are also important. Generally helical coils are preferred in compression and expansion processes, but in electromagnetic sheet metal forming process flat coils are used.

In this study, a planar spiral coil is employed to perform the forming operation. Due to limitations of the assembled structural forming area, the diameter of the forming area is se-

Table 1. Properties of the two coils that are used in this study

Parameter	Coil #1	Coil #2
Inner diameter (mm)	23.10	22.44
Number of turns	7	6
Wire width (mm)	3.00	3.00
Turn spacing (mm)	3.00	3.93
Outer diameter (mm)	107.1	105.6
Calculated length of the wire (m)	1.432	1.206
Calculated inductance (μH)	2.829	2.035

lected to be 100 mm. The spiral coil of square cross-section (1mm $\times$ 3mm) is cut from a copper sheet using a water-jet cutting machine (Fig-2). This spiral coil is then inserted in a polyamide casing and secured using a refractory material (Fig-3). This material both acts as an insulator between the coil and the sheet and prevents coil being deformed in process. The coil parameters are listed in Table-1.

In the setup, the capacitor bank consists of five capacitors ($625\mu F$ each) connected in parallel (total capacitance being $3125\mu F$) is charged to $2000V$. The measured total resistance of the circuit is 0.05Ω. Using Eq-1, the current in the system can be plotted with time as in Fig-4 for both coils. Note that, the second coil has a higher frequency: In view of Eq.2, for the first coil $\omega_0 \cong 10 \times 10^3\ rad/s$ which results in a frequency of $f_0 \cong 67\ kHz$, whereas for the second coil, these values are $\omega_0 \cong 40 \times 10^3\ rad/s$ and $f_0 \cong 249\ kHz$.

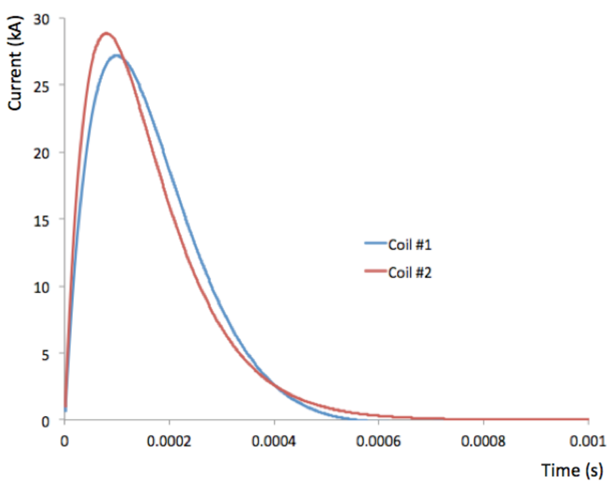

Figure 4. The time dependence of the current (calculated)

Note further that, the skin depth is evaluated through

$$\delta = \frac{1}{\sqrt{\pi f \sigma \mu}} \tag{6}$$

from which, it can be concluded that, the first coil (with lower frequency) would penetrate deeper in the given material, creating a higher magnetic pressure (if sheet thickness is larger than the skin depth). In actual figures, with aluminum, the electrical inductance is $\sigma \cong 3.5 \times 10^7\ S/m$ which results in a skin depth of $\delta \cong 0.33\ mm$ for the first coil and $\delta \cong 0.17\ mm$ for the second coil. The experiments are performed on $1\ mm$ and $1.5\ mm$ sheets, therefore, the first coil is expected to perform better.

Since the analysis of a spiral coil is not an easy task, as in most of the studies in literature, the coil will be assumed as concentric circular wires (Fig-5). Each circular wire is referred to a cylindrical coordinate system as in Fig-6.

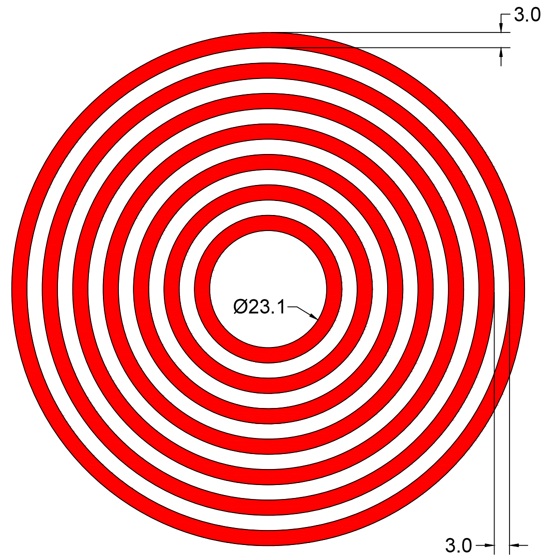

Figure 5. An idealized sketch of 7-turn coil

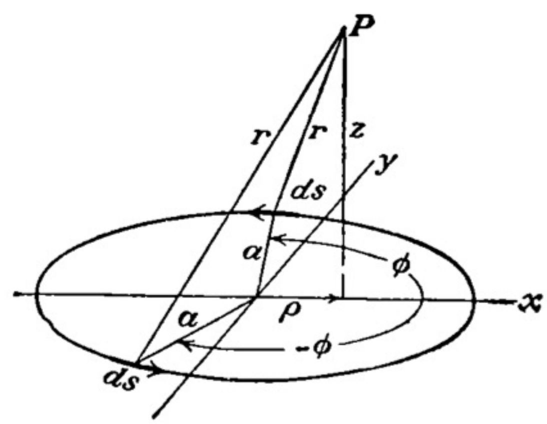

Figure 6. The definitions for a circular wire in cylindrical coordinate system [12]

The magnetic flux density in ρ and z directions can be given by [12] :

$$B_\rho = \frac{\mu I}{2\pi} \frac{z}{\rho\sqrt{(\alpha+\rho)^2+z^2}} \left[\frac{\alpha^2+\rho^2+z^2}{(\alpha-\rho)^2+z^2} E(k) - K(k) \right] \tag{7}$$

and

$$B_\rho = \frac{\mu I}{2\pi} \frac{1}{\sqrt{(\alpha+\rho)^2+z^2}} \left[\frac{\alpha^2-\rho^2-z^2}{(\alpha-\rho)^2+z^2} E(k) + K(k) \right] \tag{8}$$

In these equations, K(k) and E(k) are complete eliptic integrals of the first and second kind, and ρ, α and z are dimensions related to the circular wire (see Fig-6), μ is the dielectric permeability constant which is given as $\mu = 4\pi \times 10^{-7}$ for free space, I represents the value of the current (in A), k is a geometry-related parameter given as

$$k^2 = \frac{4\alpha\rho}{(\alpha+\rho)^2 + z^2} \tag{9}$$

Adding up the contributions coming from each of seven coils, the plot of B_ρ and B_z can be obtained as in Fig-7 and 8 for $z-$values of 2.5, 4.5 and 6.5 mm (noting that the coil has 3 mm thickness, half of which is 1.5 mm and taking three different distances from the top center of the coil: 1.0 mm, 3.0 mm and 5.0 mm).

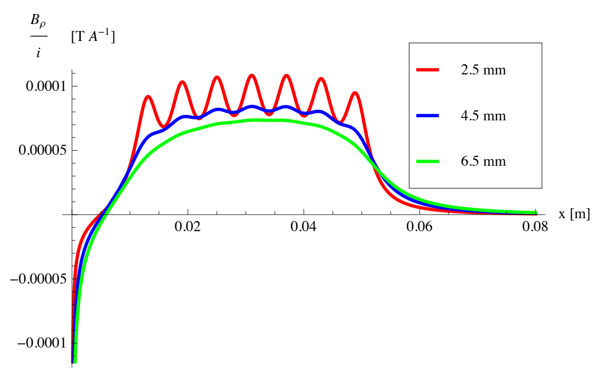

Figure 7. Plot of B_ρ

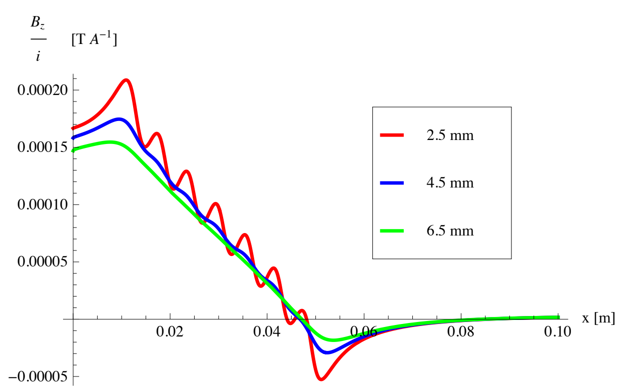

Figure 8. Plot of B_z

The electromagnetic force generated by each circular conductor depends on Br and the current (Fig 4) in the system [4].

3. Experimental studies

The circuit diagram of the setup used in the experiments is presented in Fig-9. As stated before, in the setup, the capacitor bank consists of five pulse-capacitors ($625\mu F$ each) connected in parallel (total capacitance being $3125\mu F$). The capacitor bank is charged to $1000V$ and $2000V$ in two experiments. Two coils with same cross section but different number of turns are used: Coil 1 has 7 turns, Coil 2 has 6 turns. Best results are obtained with the Coil 1, for which the properties are presented in Table-1. The results of the experiments are presented in Table-2.

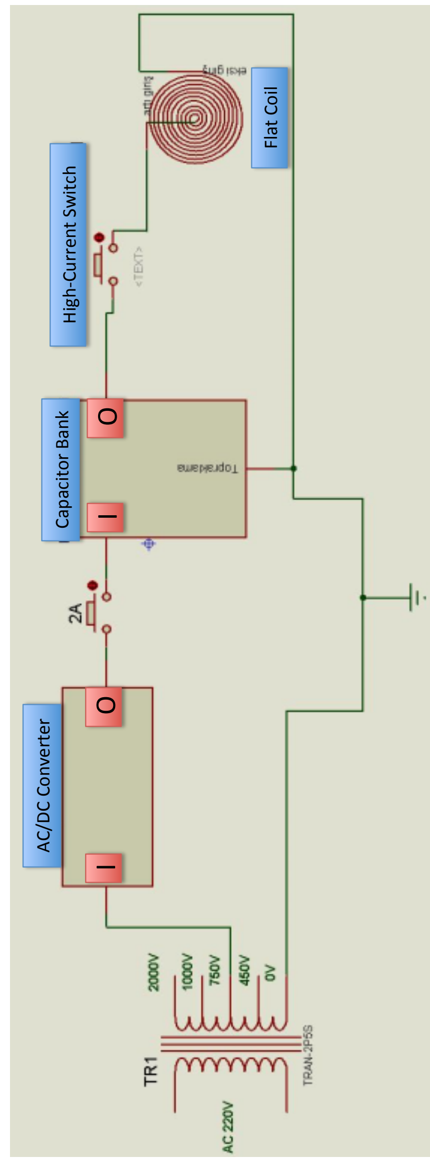

Figure 9. Circuit diagram of the setup used in the experiments

In the experiments, Aluminum 75XX series sheets of 1 mm and 1.5 mm are used. Selection of Aluminum sheets is due to good electrical conductivity and lower yield strength (when compared to steel sheets).

In the experiments, it has been seen that, although being thicker, 1.5 mm sheets are formed comparable to the 1mm thick sheets. Using conventional forming methods, it is harder to form (requires larger forces) thicker material.

4. Conclusion and Discussion

In this study a setup for forming sheet metal parts using electromagnetic field is presented. The forming setup presented is capable of bulging Aluminum sheets, yet it is possible to ex-

Table 2. Experiment results

No	Charging Voltage (V)	Metal Thickness (mm)	Coil #	Cavity Depth (mm)
1	1000	1	2	6.5
2	1000	1.5	2	7
3	2000	1.5	2	7.5
4	2000	1	1	13
5	2000	1.5	1	13.5

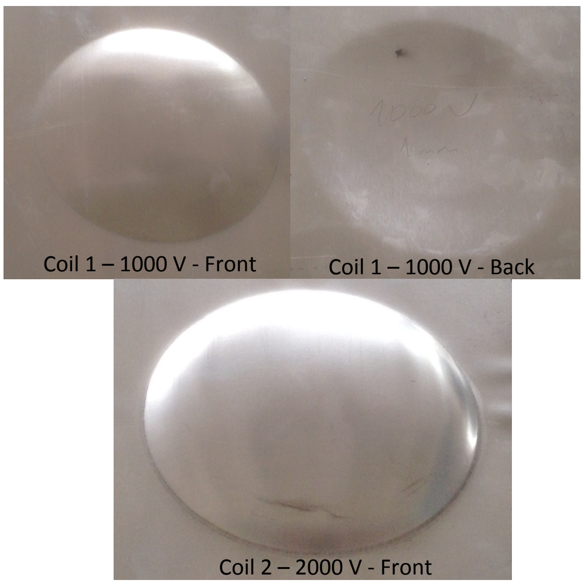

Figure 10. An example of electromagnetically bulged sheets

tend the capability of the setup with different dies and die setups (this issue is considered as a further study).

The setup consists of an R-L-C circuit where an highly damped sinusoidal oscillation of the current is obtained with tuned selection of the circuit parameters. In the setup, pulse-capacitors are used to achieve highest amplitude level of the current.

In the presented analyses, and examining the outcome of the experiments, several conclusions can be made:

- Coil design is an important issue in optimisation of the forming setup. In this study, only two different coils (6-turn and 7-turn) are employed - yet it is possible to design a different coil using the knowledge on the magnetic field density. Further analysis requires extensive numerical study, which can be considered as a later topic for this presented study.
- Since the expected pulse current is very high (approx. 25 kA - see Fig-4), it is necessary to use pulse capacitors, since other type of capacitors cannot achieve that peak, and for this reason, even if the same setup is constructed, the forming operation cannot be performed.
- To obtain such a pulse given in Fig-4, it is necessary to obtain an over-damped system, e.g., ζ should be smaller than unity. Although, this can be achieved by a good selection of L and C values, the dominant figure would be the total resistance of the setup. Therefore, precautions should be taken to minimise the total resistance.
- In the experiments, as stated before, it has been seen that thicker sheets can be formed comparable to thinner sheets. This is an important issue in ESMF, since in other forming methods, it is harder to form thicker sheet - larger forces and more expensive equipment should be employed.

To conclude, in this study, it has been seen that ESMF presents a good alternative to other forming methods.

5. References

[1] V. Psyk, D. Risch, B. Kinsey, A. Tekkaya, and M. Kleiner, “Electromagnetic forming—a review,” *Journal of Materials Processing Technology*, vol. 211, no. 5, pp. 787 – 829, 2011. Special Issue: Impulse Forming.

[2] N. Takatsu, M. Kato, K. Sato, and T. Tobe, “High-speed Forming of Metal Sheets by Electromagnetic Force,” *JSME International Journal Series III-Vibration Control Engineering Engineering for Industry*, vol. 31, pp. 142–148, MAR 1988.

[3] B. Baranoglu, E. Aydin, S. Tutuncu, and K. Y. Kocaman, “Electromagnetic bulging: A sheet metal forming process using electromagnetic field,” in *Diemolds, Antalya*, 2013.

[4] E. Paese, M. Geier, R. P. Homrich, and J. L. Pacheco, “Simplified Mathematical Modeling for an Electromagnetic Forming System with Flat Spiral Coil as Actuator,” *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 33, pp. 324–331, JUL-SEP 2011.

[5] Q. Cao, L. Li, Z. Lai, Z. Zhou, Q. Xiong, X. Zhang, and X. Han, “Dynamic analysis of electromagnetic sheet metal forming process using finite element method,” *International Journal of Advanced Manufacturing Technology*, vol. 74, pp. 361–368, SEP 2014.

[6] Q. Cao, X. Han, Z. Lai, B. Zhang, Z. Zhou, L. Qiu, and L. Li, “Effects of Current Frequency on Electromagnetic Sheet Metal Forming Process,” *IEEE Transactions on Applied Superconductivity*, vol. 24, JUN 2014.

[7] Z. Lai, X. Han, Q. Cao, L. Qiu, Z. Zhou, and L. Li, “The Electromagnetic Flanging of a Large-Scale Sheet Workpiece,” *IEEE Transactions on Applied Superconductivity*, vol. 24, JUN 2014.

[8] E. Paese, M. Geier, R. Homrich, and R. Rossi, “A coupled electric–magnetic numerical procedure for determining the electromagnetic force from the interaction of thin metal sheets and spiral coils in the electromagnetic forming process,” *Applied Mathematical Modelling*, vol. 39, no. 1, pp. 309 – 321, 2015.

[9] G. W. Harvey and D. F. Brower, “Metal forming device and method,” Mar. 28 1961. US Patent 2,976,907.

[10] D. F. Brower, “Forming device and method,” Oct. 18 1966. US Patent 3,279,228.

[11] C. Beerwald, A. Brosius, M. Kleiner, and V. Psyk, “Einfluss des magnetischen druckes bei der elektromagnetischen blechumformung,” in *2. Kolloquium Elektromagnetische Umformung, Dortmund*, 2003.

[12] W. R. Smythe, *Static and Dynamic Electricity*. Hemisphere Publishing Corporation, 3 ed., 1989.