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Numerical Investigation on Forming Conditions Impact in Electromagnetic Tube Expansion Performance

Ilhem Boutana*(C.A.) and Mohamed Rachid Mekideche*

Abstract: *Electromagnetic Tube Expansion* (EMTE) is a *high-velocity forming* process that utilizes transient magnetic fields to plastically deform *tubular* workpieces without physical contact. The process requires the generation of large currents via a *capacitor bank*, producing intense magnetic pressures to achieve deformation. While EMTE offers significant advantages in *precision* and *efficiency*, a comprehensive understanding of the interplay between key working conditions and deformation mechanisms remains crucial for optimizing its performance. This paper presents a numerical investigation into the effects of critical working conditions on the electromagnetic tube expansion process. Using a coupled finite element model, the transient magnetic field and resultant tube deformation are analyzed under varying conditions. The results provide insights into the relationship between process parameters and deformation outcomes, highlighting the potential for optimizing EMTE systems for enhanced *efficiency* and *uniformity*. This study contributes to advancing the *theoretical* and *practical* understanding of EMTE, by offering guidance for the design of more effective forming strategies and equipment.

Keywords: Electromagnetic Forming, Finite Element Analysis, Plastic Deformation, Tube Expansion.

1 Introduction

NOWADAYS, *Electromagnetic Forming* (EMF) has emerged as a cutting-edge manufacturing technique in the active literature (e.g., [1-5]), by leveraging the *high-velocity deformation* of materials induced by transient magnetic fields. As a *non-contact* and *high-precision* forming process, EMF offers distinct advantages over conventional forming methods, including *reduced spring-back*, *improved material flow*, and the ability to process *lightweight* and *hard-to-form* materials such as aluminum alloys (e.g., [6,7]). Among the various applications of EMF, *Electromagnetic Tube Expansion* (EMTE) has gained significant attention due to its potential to fabricate tubular components with complex geometries for industries such as *automotive*, *aerospace*, and *energy* (e.g., [8-10]).

The EMTE process involves the interaction of electromagnetic forces and mechanical deformation, requiring a coupled analysis of the electromagnetic field and the workpiece's dynamic response. This coupling is essential for accurately capturing the complex interactions that govern the deformation process. While numerous studies have utilized *Finite Element Method Analysis* (FEM) to model electromagnetic forming devices, many have focused primarily on *single-coil* configurations or *material-specific* behavior. The role of critical process parameters, such as the capacity of the capacitor bank, discharge energy, and coil dimensions, on the magnetic force distribution and resulting tube deformation remains inadequately explored.

The magnetic force exerted on tubular workpieces during EMTE is directly related to the current density and magnetic flux density within the tube, both of which are influenced by the electrical and geometric configurations of the forming apparatus. Understanding how these parameters interact to control the deformation process is crucial for optimizing the design and efficiency of EMTE systems. This need for optimization has driven interest in developing numerical models that integrate electromagnetic field analysis with plastic

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* The authors are with the Laboratory of Electrical Engineering and Industrial Electronics, Faculty of Science and Technology, University of Jijel, Jijel, 18000, Algeria
E-mail: hafsaoui@univ-jijel.dz; mohamed.mekideche@univ-jijel.dz
Corresponding Author: Ilhem Boutana.

deformation mechanics to simulate the forming process under varying conditions.

Moreover, the growing demand for *lightweight*, *durable*, and *highly customizable* components in industries has driven the need for innovative manufacturing techniques. Electromagnetic tube expansion offers significant advantages over state-of-the-art methods. These include reduced material wastage, enhanced forming precision, and the ability to process materials with challenging geometries and mechanical properties. However, the complex interplay between electrical, magnetic, and mechanical phenomena in EMTE remains poorly understood, particularly concerning the influence of key process parameters. Achieving optimal deformation while maintaining structural integrity and minimizing energy consumption presents a significant challenge.

Furthermore, the advancement of simulation technologies, such as finite element analysis, provides an unprecedented opportunity to study these intricate processes in detail, reducing the reliance on costly and time-consuming experimental trials. This research aims to harness these tools to bridge the gap in understanding, offering insights that can lead to improved design and control of EMTE systems. By enhancing the *efficiency*, *precision*, and *reliability* of EMTE, this study contributes to the development of more sustainable manufacturing processes, aligning with the global push for greener, more resource-efficient production methods. This work is motivated by the desire to innovate and improve not only the technical aspects of forming technologies but also their broader impact on industrial practices and environmental sustainability.

1.1 Summary of Paper Contributions

Following these considerations, the primary contribution of this work lies in advancing the understanding and optimization of electromagnetic tube expansion through a comprehensive numerical investigation. Unlike previous studies that focus on isolated aspects of the process, this research integrates *electromagnetic field analysis* with *plastic deformation mechanics* to provide a holistic understanding of the forming dynamics. The proposed methodology leverages coupled finite element analysis to simulate and predict the effects of critical parameters, such as discharge circuit capacity, energy levels, and coil geometry, on the deformation process. In addition, this research is a short version of our previous work [11], where we explored in detail electromagnetic tube expansion based on a field concentrator. Overall, the objectives of this research are as follows:

- *Influence of Key Parameters Analysis*: evaluating the impact of varying discharge energy, capacitor bank capacity, and coil dimensions on magnetic forces, current densities, and resulting deformation of tubular workpieces.
- *Robust Numerical Models Development*: constructing a coupled numerical framework that integrates transient electromagnetic field equations with plastic deformation mechanics for accurate simulation of the tube expansion process.
- *Electromagnetic Forming Process Optimization*: identifying the optimal configuration of electrical and geometric parameters that maximizes deformation efficiency while ensuring uniformity and precision.
- *Validation of Numerical Predictions*: comparing the results of the developed model with existing experimental data and theoretical analyses, to ensure its reliability and applicability for practical implementations.

1.2 Paper Organization

The remaining part of this paper is organized as follows. Section 2 reviews some of the most relevant and significant related work for our research. In Section 3, we introduce our methodology of electromagnetic tube expansion, along with mathematical and geometrical models. After that, in Section 4, we present and discuss our obtained results. Finally, Section 5 provides conclusions and possible directions for future work.

2 Related Work

In this Section, we review some of the most relevant and significant related work for our research. This analysis provides a comprehensive overview of recent electromagnetic tube expansion proposals.

A new approach, termed *Electromagnetic Tube Expansion with Axial Compression* (EMTEAC), is proposed in [12] to mitigate the issue of excessive wall thickness reduction observed in traditional electromagnetic tube expansion. This method incorporates additional coils at both ends of the tube, generating axial electromagnetic forces that supplement the radial force produced by the main driving coil. Finite element analysis is utilized to evaluate the magnetic flux density distribution and the electromagnetic forces exerted by the three coils. The simulation findings indicate that the axial electromagnetic force in EMTEAC is nearly seven times higher than that in conventional EMTE, thereby improving material flow during the expansion process.

[13] presents a novel *dual-coil electromagnetic tube forming* technique designed to enhance control over the workpiece profile in electromagnetic forming. This approach introduces automatic feedback control of the Lorentz force distribution, ensuring more uniform tube

deformation. Experimental and simulation analyses confirm the method's effectiveness, demonstrating how key electromagnetic parameters influence the deformation behavior of AA6061-O aluminum alloy tubes. By dynamically adjusting the radial Lorentz force distribution, this technique achieves approximately 2.7 times greater deformation uniformity compared to conventional single-coil electromagnetic forming.

In [14], they present a significant advancement in electromagnetic forming by focusing on improving process efficiency and minimizing energy losses. A key aspect of this study is the investigation of how the die material influences the deformation of an aluminum tube during EMF. By comparing two dies with identical geometries but different materials—*nylon* and *steel*—the research demonstrates a 5% greater deformation with the nylon die under the same discharge energy. This highlights the crucial role of the die material in optimizing EMF efficiency. Furthermore, finite element simulations are conducted, showing 94% agreement with experimental results, reinforcing the study's findings.

In [15], a *streamlined* and *precise* theoretical model is introduced to bridge *electrical* and *thermal* data in the electromagnetic tube-forming process. This model significantly enhances the speed of temperature estimation for the workpiece compared to finite element simulations or experimental methods. The study develops a *one-dimensional semi-coupled electrothermal field* model, incorporating both electromagnetic and thermomechanical sub-models. By examining critical process parameters and their interactions, the research offers a comprehensive understanding of the electrothermal dynamics in electromagnetic tube forming.

[16] investigates how *inner diameter* (ID), *outer diameter* (OD), the *effective number of turns*, and *cable connections influence coil behavior*. The study evaluates coil performance by analyzing variations in inductance, resistance, current pulse, and tube deformation. Experimental assessments examine how changes in ID, OD, and cable configuration affect inductance and resistance. By establishing correlations between coil performance, theoretically and experimentally derived current pulses, and system inductance, the research highlights key influences on electromagnetic forming. The results indicate that minor adjustments in diameter and effective turns can lead to current pulse amplitude variations of approximately $30\,kA$. Additionally, integrating an extra parallel discharge cable increases current and frequency by about 26% and 23%, respectively.

[17] addresses the challenge of *inhomogeneous axial deformation* in conventional electromagnetic tube expansion, a result of end effects produced by traditional helix coils. To overcome this issue, the study proposes a novel concave coil structure as an alternative to the standard helix coil, aiming to optimize the radial electromagnetic force distribution on the tube. This modification is expected to enhance the uniformity of axial deformation. To evaluate and quantify the improvement, the research introduces a new deformation uniformity criterion, known as the *R-L criterion*.

3 Methodology

In this Section, we present the fundamental principles underlying electromagnetic tube expansion and detail the methodology employed in this study. This includes the theoretical foundation of the process, the governing equations derived from Maxwell's equations, and the design of the geometrical and mathematical models necessary for numerical simulations.

Electromagnetic tube expansion is a process that uses transient high-intensity magnetic fields to plastically deform tubular workpieces. This process relies on the rapid discharge of energy stored in a capacitor bank, generating a magnetic force that induces deformation. The performance of the process is influenced by multiple factors, such as the electrical circuit parameters, coil geometry, and the material properties of the tube.

In this research, we propose a coupled numerical approach integrating electromagnetic field analysis and plastic deformation mechanics to model the tube expansion. The methodology includes solving the *magnetodynamic* equations to calculate the transient magnetic forces, applying these forces as input to a finite element analysis model, and simulating the deformation of the tube under various conditions. The mathematical model includes transient analyses of the electromagnetic field, where Maxwell's equations are discretized to compute the magnetic flux density and current density distribution. The deformation mechanics are modeled using equilibrium equations that account for stress, strain, and electromagnetic force densities. The system's geometrical representation and boundary conditions are carefully defined to ensure accurate simulation results.

This methodology allows us to explore the effects of varying working conditions, such as the capacitor bank's capacity, discharge energy, and coil dimensions, on the electromagnetic forces and resulting tube deformation. By examining these factors, we aim to optimize the forming process and improve its efficiency and precision.

3.1 Electromagnetic Field Analysis

Here, we delve into the underlying principles governing the electromagnetic field during tube expansion processes. This section outlines the mathematical models and equations essential for transient magnetic field analysis and their implementation in axisymmetric systems. By solving Maxwell's equations, we develop formulations to determine the relationship between current density, magnetic flux, and the forces exerted during the forming process.

The electromagnetic tube expansion process relies on the generation of intense, transient magnetic fields that induce eddy currents in the conductive tube. These currents interact with the magnetic field, producing *Lorentz forces* that act radially outward and drive the plastic deformation of the tube. To accurately quantify these electromagnetic forces and their *spatial-temporal distribution*, a rigorous numerical solution of Maxwell's equations is required.

In this research, the *electromagnetic field analysis* is performed in a *two-dimensional axisymmetric domain* using a finite element formulation. The simulation focuses on solving the *time-dependent magneto-dynamic equations* to evaluate the *magnetic vector potential* A, from which the *magnetic flux density* B, *current density* J, and *electromagnetic force density* are derived. These computed force fields serve as the loading input for the mechanical model governing the tube's plastic deformation, thus establishing a strong coupling between the *electromagnetic* and *mechanical* domains.

3.1.1 Governing Equations

The transient magnetic field is governed by Maxwell's equations, and the magnetic vector potential formulation is used:

$$\sigma \frac{\partial A}{\partial t} + curl\left(\frac{1}{\mu}.curl\ A\right) - \sigma.v.(curl\ A) = J_{ex} \quad (1)$$

where A is the magnetic vector potential, J_{ex} denotes the current density in the coil, μ represents the magnetic permeability, σ is the electrical conductivity, v is the velocity of the workpiece being joined, $curl\ A$ is the vector operator that describes the circulation (i.e., the movement) of A.

In *axisymmetric configurations*, only the azimuthal component A_θ is *non-zero*. This simplifies the problem to a scalar formulation:

$$\sigma \frac{\partial A_\theta}{\partial t} - \frac{1}{\mu.r}\frac{\partial}{\partial r}\left(r\frac{\partial A_\theta}{\partial r}\right) - \frac{1}{\mu}\left(\frac{\partial^2 A_\theta}{\partial z^2}\right) = J_{\theta ex} \quad (2)$$

This partial differential equation is discretized using the finite element method to compute the evolution of $A_\theta(r,z,t)$ over time. The magnetic flux density vector is then obtained via:

$$B = curl\ A \quad (3)$$

The key coupling mechanism between the electromagnetic field and the mechanical deformation lies in the *Lorentz force*, which acts as a distributed body force within the tube:

$$F = J_{ind}\ X\ B \quad (4)$$

In the conductive tube, the time-varying magnetic field induces eddy currents J_{ind}, primarily azimuthal, which interact with the radial and axial components of the magnetic field. This interaction produces a net radial force, responsible for expanding the tube.

3.1.2 Geometrical Models

The tube expansion system is illustrated in Fig. 1, whilst the basic dimensions of the electromagnetic forming system are given in Table 1. It is the same system used experimentally [18].

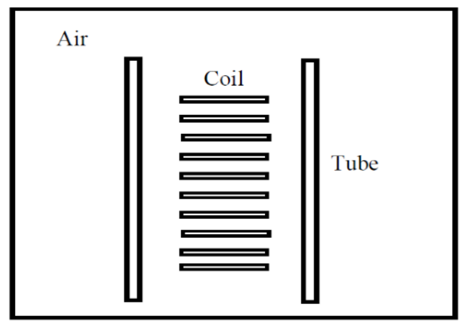

Fig 1. Forming Coil and Tubular Workpiece in Electromagnetic Forming.

As shown in Fig. 1, the simulation domain includes three sub-regions: the solenoidal coil (current source), the deformable tube (conductor), and the surrounding air. Only a quarter of the model is considered, exploiting symmetry in both geometry and boundary conditions.

Table 1. Numerical System Dimensions.

Parameter	Value $[mm]$
Coil Length	$40 - 47 - 54$
Coil Radius	24.8
Tube Length	48
Tube Inner Radius	30
The gap between Coil and Tube	2.6

Moreover, the following *appropriate electromagnetic boundary condition*s are applied (see Fig. 2):

- Zero normal flux at symmetry boundaries.
- Continuity of tangential fields across material interfaces.
- Time-varying current source is applied to the coil.

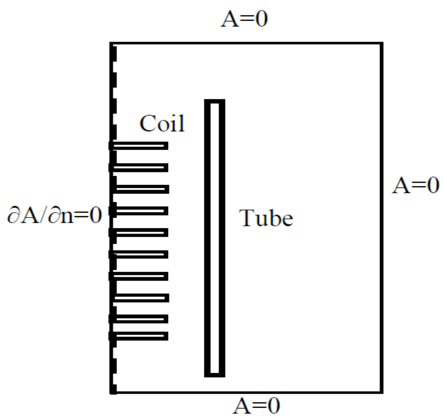

Fig 2. Our Electromagnetic Field Analysis Model.

3.1.3 Discharge Current

The primary current flowing in the forming coil is generated by the transient phenomenon of discharge from the capacitor bank.

From an electrical point of view, the forming coil and the workpiece have transformer coupling. The equivalent circuit diagram of the discharge apparatus is shown in Fig. 3 with parameters listed in Table 2.

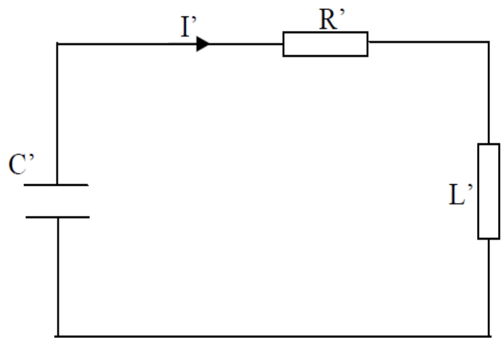

Fig 3. Electrical Equivalent Circuit for Electromagnetic Forming.

The waveforms of the discharge currents are obtained using the following equation based on the equivalent circuit (see Fig. 3).

Table 2. Parameters of the Circuit.

Parameter	Value
Resistance	$25.5 m\Omega$
Inductance	$2\mu H$
Capacity	$40\mu F - 1600\mu F$
Voltage	$6KV - 24KV$
Energy	$720J - 2880J$

The electromagnetic forming components can be lumped together and simplified into a circuit containing a capacity C, resistance R, and inductance L. The behavior of such a system is described by the following differential equation:

$$\left(\frac{d^2I(t)}{dt^2}\right) + 2 * \xi * \omega * \left(\frac{dI(t)}{dt}\right) + \omega^2 * I(t) = 0 \qquad (5)$$

where $I(t)$ is the current caused by discharging capacity, ξ is the damping term given by $\xi = \left(\frac{1}{2}\right) * R * (\frac{C}{L})^{\frac{1}{2}}$, ω is the natural frequency given by $\omega = (\frac{1}{L*C})^{\frac{1}{2}}$.

In electromagnetic forming, ξ is less than *one*, which represents an *under-damped system*. Solving the above differential equation provides the current as a function of time:

$$I(t) = V_0 * \left(\frac{C}{L}\right)^{\frac{1}{2}} * \exp(-\xi * \omega * t) * sin(\omega_o t) \qquad (6)$$

such that V_0 is the original voltage cross-capacity.

3.2 Plastic Deformation Analysis

Once the electromagnetic field analysis provides the *spatial* and *temporal* distribution of the Lorentz forces acting on the tube, the mechanical response of the workpiece must be computed to evaluate the resulting deformation. The tube is modeled as an *elastoplastic mater*ial subjected to dynamic loading due to the transient electromagnetic forces. This Section outlines the *governing mechanical equations*, *material behavior assumptions*, and the numerical strategy employed for deformation analysis.

The mechanical behavior of the tube during the electromagnetic tube expansion process is governed by the *dynamic equilibrium equation*, expressed as:

$$\rho \frac{\partial^2 u}{dt^2} - \nabla.\Sigma = F \qquad (7)$$

where ρ is the density, u represents the displacement vector, Σ is the stress tensor, and F is the electromagnetic force density.

This *second-order differential equation* describes the motion of the tube under the influence of both *internal stresses* and externally applied electromagnetic forces.

The *total strain tensor* ε is derived from the displacement field via the *kinematic relations in cylindrical coordinates*. For axisymmetric problems, the relevant components are:

$$\begin{cases} \varepsilon_r = \frac{\partial u_r}{\partial r} \\ \varepsilon_z = \frac{\partial u_z}{\partial z} \\ \varepsilon_{rz} = \varepsilon_{zr} = \frac{1}{2}.\left(\frac{\partial u_r}{\partial z} + \frac{\partial u_z}{\partial r}\right) \end{cases} \qquad (8)$$

with:

$$\varepsilon = \varepsilon_{el} + \varepsilon_{th} + \varepsilon_p \quad (9)$$

The electromagnetic force density, computed from the electromagnetic model, is applied as a body force load in the mechanical domain at each time step.

The *electromagnetic* and *mechanical* models are solved in a *sequential weakly coupled approach*. *Time-dependent electromagnetic force* is mapped spatially onto the mesh of the tube. And then, the mechanical solver computes displacements $u(r, z, t)$, strains, and stresses accordingly.

The mesh resolution and time step are selected to ensure numerical stability and accurate capture of the deformation wave propagation, considering the Courant condition for explicit solvers.

4 Results and Discussions

In this Section, we present and analyze the results of the numerical simulations performed to study the effects of various working conditions on electromagnetic tube expansion. The discussion focuses on the relationships between key parameters, such as capacitor bank capacity, discharge energy, and coil length, and their influence on magnetic forces and tube deformation.

A transient analysis of the aluminum tube expansion process using a solenoidal coil is presented, considering the effects of various key parameters. This study employs a coupled numerical model based on finite element dynamic simulations to capture the interaction between electromagnetic and mechanical phenomena. The magnetic forces, computed through electromagnetic field analysis, serve as source terms for the mechanical deformation model, ensuring an integrated and accurate representation of the tube expansion process.

4.1 Effect of Discharge Circuit Capacity

Here, we analyze the impact of the capacitor bank capacity on the electromagnetic tube expansion process. The capacity of the discharge circuit is a key parameter influencing the discharge current waveform, magnetic force, and the resulting deformation of the tubular workpiece. As the capacitor capacity increases, the energy stored in the circuit rises, resulting in longer discharge durations and smoother current waveforms. This leads to an increase in the magnetic pressure applied to the workpiece, which enhances deformation. However, higher capacities also reduce the peak current amplitude and delay the onset of deformation due to the extended discharge period.

For higher capacities, the magnetic force becomes more pronounced, enabling greater deformation at the cost of reduced process speed. This trade-off must be carefully optimized for applications requiring precise control.

Fig. 4 shows the calculated current waveforms obtained using Equation (2) as a function of the capacitor bank capacity. With an increase in capacity, the wave periods become longer, while the current amplitudes decrease, reflecting the influence of higher energy storage on the discharge characteristics.

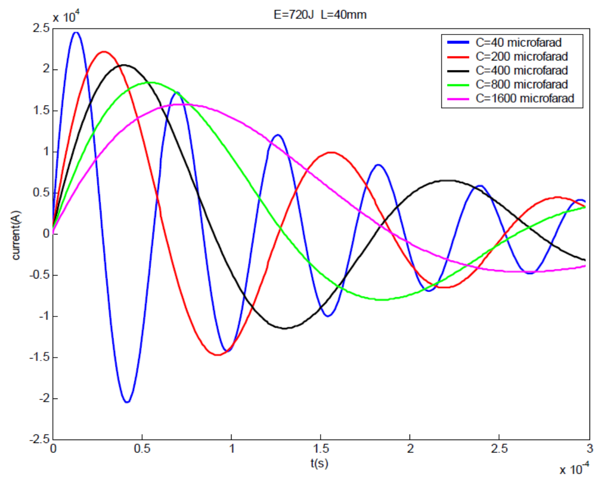

Fig 4. Waveforms of Current for Various Capacities on $40mm$ Coil.

Fig. 5 presents the maximum calculated current values for capacities ranging from $C = 40\mu F$ to $C = 1600\mu F$ across various coil lengths.

The results indicate that as the coil length increases, leading to higher inductance and resistance, the maximum current values decrease. These findings are consistent with observations reported in [19], which confirms the reliability of the analysis.

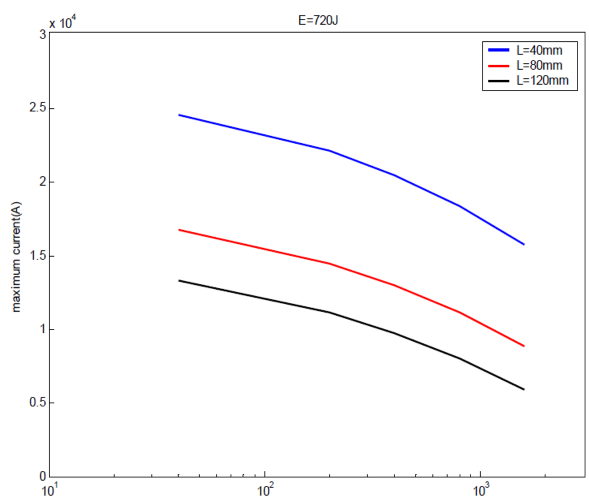

Fig 5. Variation of Maximum Current for Capacity by Several Coil Lengths.

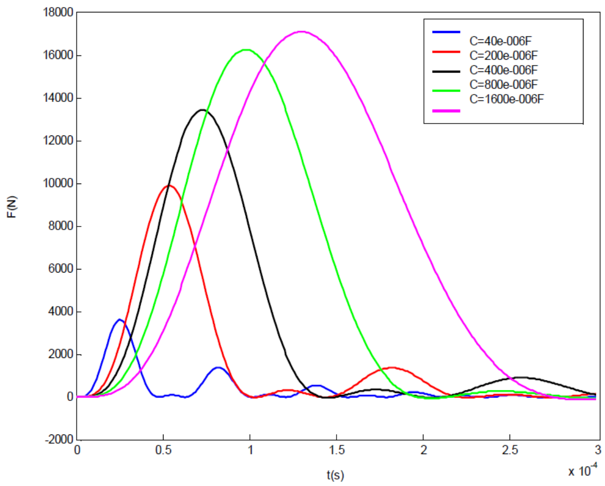

Fig 6. Magnetic Force for Various Capacities as a Function of Time (Coil Length $40mm$, Charged Energy $720J$).

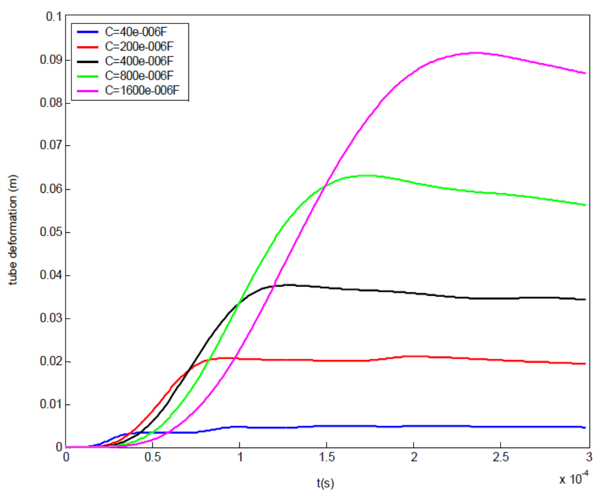

Fig 7. Tube Deformation for Various Capacities on $40mm$ Coil and $720J$ Energy.

Moreover, the effects of varying capacitor bank capacity on the magnetic force and tube deformation, calculated at a charged energy of $720J$ and a coil length of $40\,mm$, are illustrated in Fig. 6 and Fig. 7, respectively.

As it can be highlighted from this first investigation, the magnetic force increases with the capacitor bank capacity, as it is directly proportional to the induced current density and magnetic flux density. At $C = 1600\mu F$, the maximum magnetic force is approximately five times greater than that at $C = 40\mu F$. However, the frequency of the magnetic force at $C = 1600\mu F$ is significantly lower, being only one-sixth of the frequency observed at $C = 40\mu F$.

Regarding tube deformation, it is calculated at the center of the tube and reaches its maximum magnitude when the capacitor capacity is at its highest. However, the onset of deformation is delayed as the capacity increases. For instance, deformation begins at approximately $10\mu s$ for $C = 40\mu F$, $15\mu s$ for $C = 400\mu F$, and $35\mu s$ for $C = 1600\mu F$. These findings highlight the significant influence of capacitor bank capacity on tube expansion dynamics at a fixed-charged energy.

4.2 Effect of Charged Energy

The effect of charged energy on the electromagnetic tube expansion process is a crucial aspect of this study, as it directly influences the magnetic forces and deformation characteristics of the tube. Charged energy, supplied by the capacitor bank, determines the intensity of the discharge current and, consequently, the magnitude of the magnetic forces acting on the workpiece.

The relationship between charged energy and the forming process is further complicated by the dynamic behavior of the inductor current and the non-linear response of the workpiece material under rapidly changing magnetic forces. Variations in the inductor current, magnetic force, and tube deformation, as functions of the forming apparatus energy, highlight critical aspects of the process, providing insights into the optimization of energy input for achieving desired deformation outcomes.

Fig. 8 presents the variations in inductor current with respect to different energy levels, demonstrating the transient nature of the current and its peak value as a function of the charged energy. Fig. 9 shows the corresponding magnetic forces acting on the tube, revealing how energy levels modulate the intensity and distribution of these forces. Finally, Fig. 10 depicts the resulting tube deformation, highlighting the influence of energy input on the expansion process.

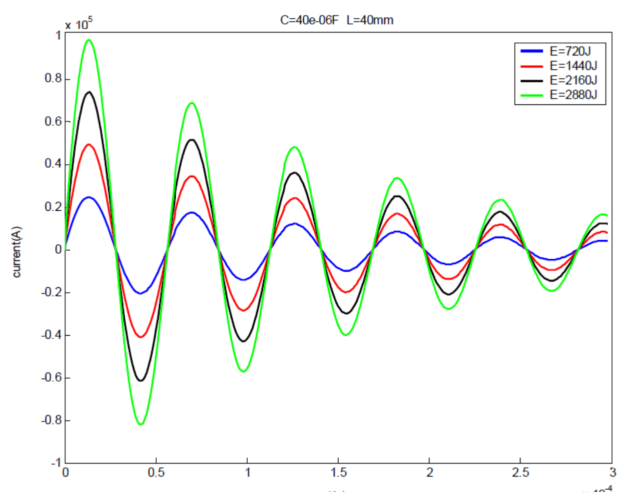

Fig 8. Current in the Coil for Various Charged Energy on $40mm$ Coil and Capacity of $40\mu F$.

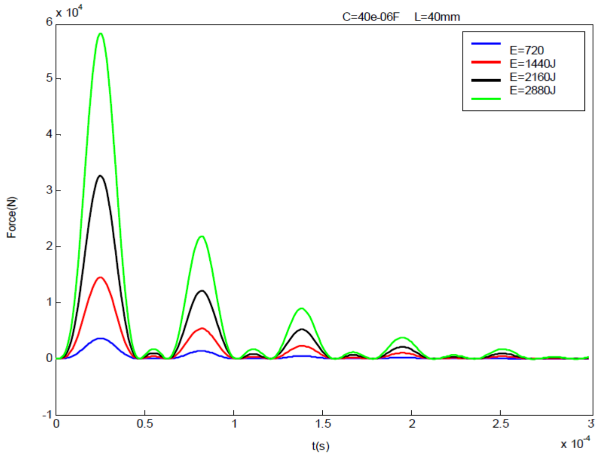

Fig 9. Relationship of Magnetic Force for Time on $40mm$ Coil and Capacity of $40\mu F$.

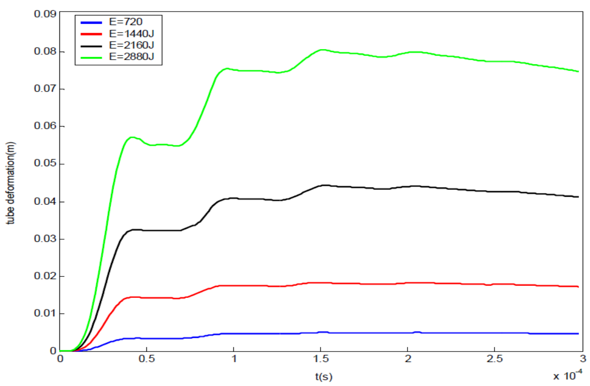

Fig 10. Tube Deformation for Various Charged Energies on $40mm$ Coil and Capacity of $40\mu F$.

As a conclusion from this study, the current in the forming coil increases proportionally with the circuit energy. As a result, the magnetic force exerted on the workpiece and the resulting tube deformation become significantly greater as the circuit energy increases. For instance, at $E = 2880J$, the maximum deformation at the center of the tube is approximately 20 times larger than that observed at $E = 720J$, given a capacitor capacity of $C = 40\mu F$ and a coil length of $40\ mm$.

These findings indicate that higher energy levels substantially enhance deformation capabilities. However, when the capacitor bank is excessively charged, achieving stable and precise tube formation may become challenging, underscoring the need for careful energy optimization in the forming process.

4.3 Effect of Coil Length

Here, we investigate the influence of coil length on the electromagnetic tube expansion process. The coil length plays a significant role in determining the distribution of the magnetic field along the length of the tube, which in turn affects the uniformity and magnitude of the tube deformation.

Fig. 11 illustrates the variations in calculated deformation over time at the center of the tube for three different coil lengths. The results indicate that the deformation at this specific point shows minimal variation across the three cases, suggesting that the coil length has a limited effect on the deformation magnitude at the tube's center.

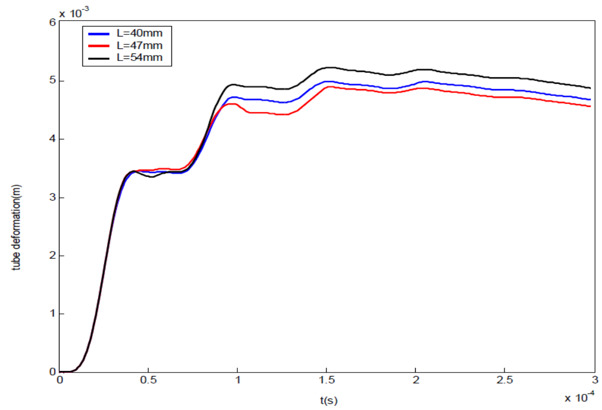

Fig 11. Deformation at the Centre of the Tube for Three Lengths of Coil.

On the other hand, Fig. 12 highlights the differences in the forming shapes of bulged tubes for various coil lengths.

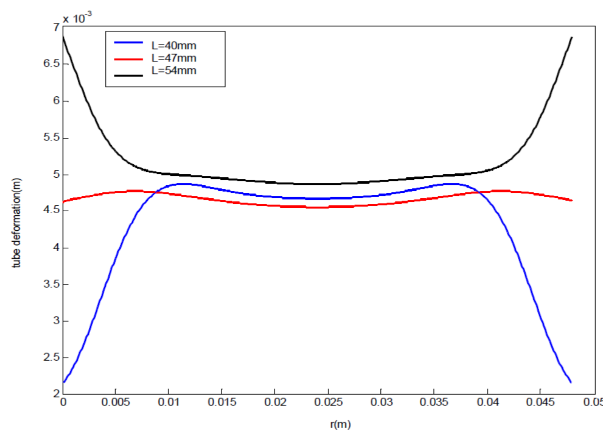

Fig 12. Forming Shapes for Various Coil Lengths.

As shown in Fig. 12, when the coil is shorter than the tube ($L = 40mm$), the bulge height is localized near the region directly in front of the coil (blue line). For a coil length equal to the tube ($L = 47mm$), the expansion is nearly uniform along the entire length of the tube (red line). In the third case, where the coil length exceeds that of the tube ($L = 54mm$), the deformation pattern exhibits a peak effect, as shown by the black line, indicating concentrated deformation at specific regions. These results demonstrate the significant influence of coil length on the deformation distribution in electromagnetic tube expansion.

4.4 Discussion and Remarks

In this Section, we discuss our obtained numerical results, along with a comparative analysis against findings from relevant studies in the active literature. In our comparison, we compare our obtained results with those reported in previous experimental studies (e.g., [20,21]).

Specifically, in their work [20], the authors present a comprehensive investigation into the electromagnetic tube expansion process, structured in three main phases. Initially, the authors developed a numerical method to solve the electromagnetic problem, implementing an *in-house FORTRAN code tailored for electromagnetic forming*. This code was then validated through a *comparative analysis with the open-source finite element software FEMM*, as well as against experimental data available in the literature. In the subsequent phase, the validated electromagnetic model was integrated into the commercial finite element software *ABAQUS/Explicit* to simulate the electromagnetic tube bulging process using an axisymmetric model. The simulations focused on *Al 1050 Aluminium tubes* with a *thickness of 1.0 mm*.

On the other hand, [21] investigates the electromagnetic forming process, with a particular focus on the *solenoidal coil method used for tube bulging*. The authors emphasize that successful tube deformation is highly dependent on specific process parameters; for instance, high charging levels of the capacitor bank do not necessarily lead to effective forming, even when substantial current is delivered to the coil. To address this, the study introduces an analytical model that accounts for the dynamic behavior of the magnetic field and skin depth, from which magnetic pressure is derived. Using this model, both *analytical* and *experimental* investigations were conducted to evaluate the effects of varying process parameters, such as *capacitor bank capacity* and *coil length, on forming efficiency*.

Table 3 presents a comparison between the results obtained from our numerical model and those reported in previous experimental studies in terms of capacitor bank capacity. Despite differences in system configurations, such as inductor geometry, dimensions, and generator power (e.g., coil length, charged energy) [20,21]. The results demonstrate good agreement, thereby validating the influence of the capacitor bank capacity.

Table 3. Comparison Between our Model and those of Previous Work in Terms of Capacitor Bank Capacity.

Model	Discharging Capacity $[\mu F]$	Coil Length $[mm]$	Charged Energy $[J]$	Max Discharge Current I_{max} $[10^4 A]$	Max Magnetic Force F_{max} $[10^2 N]$	Max Tube Deformation $[mm]$
Our Model	40	40	720	2.4	3500	5
	200			2.25	10000	20
	400			2	13000	35
	800			1.75	16000	60
	1600			1.5	17000	90
[20]	20	100	1000	1.8	/	/
	100			1.75		
	200			1.7		
	310			1.6		
	800			1.4		
	1600			1.15		
[21]	20	100	1000	2	/	/
	100			1.8		
	200			1.6		
	310			1.5		
	800			1.25		
	1600			1.1		

This observation is also supported by theoretical analysis, as the capacitance significantly affects the damping factor of the discharge current, influencing the system's overall energy delivery characteristics. Specifically, an increase in capacitance results in a lower peak discharge current due to the prolonged energy release over a longer pulse duration. This reduction in current amplitude alters the electromagnetic force generation during the forming process. In contrast, both the peak magnetic force and the extent of tube expansion demonstrate a direct correlation with the total energy stored in the capacitor bank, as a larger capacitance allows for greater energy accumulation. Consequently, optimizing the capacitor bank capacity becomes a critical factor in controlling both the force intensity and the material deformation outcomes in electromagnetic forming processes.

An additional critical parameter that significantly influences the magnetic expansion of tubes is the power of the discharge generator. A brief comparison of our numerical results with those reported in [20,21] confirms this effect, despite variations in other geometric and physical parameters of the discharge generator (see Table 4). Indeed, it is theoretically evident that higher energy supplied by the discharge generator results in a stronger discharge current, leading to more intense magnetic forces and a more pronounced tube expansion.

Another parametric study focuses on the geometric parameter, i.e., the inductor length, which has a notable influence on the tube expansion behavior. The results indicate that the reliability and uniformity of tube expansion improve with increasing inductor length.

Table 4. Comparison Between our Model and those of Previous Work in Terms of Charged Energy.

Model	Charged Energy $[J]$	Coil Length $[mm]$	Discharging Capacity $[\mu F]$	Max Discharge Current I_{max} $[10^4 A]$	Max Magnetic Force F_{max} $[10^2 N]$	Max Tube Deformation $[mm]$
Our Model	720	40	40	2.5	35	5
	1440			5	150	15
	2160			7	325	45
	2880			9.5	575	80
[20]	1000	100	100	/	/	7
	2000					10
[21]	1000	100	100	/	/	21
	2000					22

A longer inductor promotes a more effective magnetic coupling over a larger axial region of the tube, resulting in a more controlled and symmetric expansion. However, this parameter particularly affects the final shape of the tube, as the expansion tends to be concentrated in the region directly opposite the coil (see Table 5).

As a conclusion from this comparison, and according to both the literature and the fundamental principles of electromagnetic forming, the most influential parameters are the *capacity* of the discharge capacitor bank and the *energy* (power) of the pulse generator. This observation has been thoroughly validated through the numerical analyses conducted in this study. Specifically, increasing the capacitance enhances the discharge current and magnetic field intensity, which in turn amplifies the magnetic forces acting on the tube, thereby promoting greater expansion. Similarly, higher generator energy results in stronger magnetic fields and more effective deformation. In addition to these electrical parameters, the geometry of the inductor, particularly its shape and length, plays a crucial role in determining the final deformation profile of the tube, especially in terms of expansion uniformity.

Additionally, we perform a qualitative comparison between our approach and some work from the active literature. Specifically, regarding [17], the study investigates electromagnetic tube expansion using *concave* and *helical coils*. Through both simulation and experimental analyses, the authors examined the deformation homogeneity of the tube under the influence of these two coil geometries. The findings concluded that the use of a *multilayer concave coil* can further enhance the uniformity of deformation over a larger axial range. However, our numerical results indicate that even a *helical* (*spiral*) *coil* can produce a highly uniform tube expansion, by considering that the inductor length is carefully optimized.

As for [13], the study introduces a *novel dual-coil electromagnetic forming technique* aimed at enhancing control over the workpiece profile. By implementing an automatic feedback mechanism to regulate the *Lorentz force distribution*, the authors achieved significantly improved *deformation uniformity in AA6061-O aluminum tubes*. Both experimental and simulation results validate the effectiveness of this method, particularly in terms of dynamic control of the radial Lorentz force. In contrast, our numerical approach demonstrates that a high degree of deformation uniformity can also be attained using a *single helical coil*, provided that critical design parameters, most notably the inductor length, are carefully optimized. While [13] relies on complex *dual-coil configurations* and *active force regulation*, our findings suggest that comparable results can be achieved with simpler coil geometries and by leveraging a rigorous parametric design strategy.

Table 5. Comparison Between our Model and those of Previous Work in Terms of Coil Length.

Model	Coil Length $[mm]$	Charged Energy $[J]$	Discharging Capacity $[\mu F]$	Max Tube Deformation $[mm]$
Our Model	40	720	40	5
	47			4.75
	54			5.25
[20]	200	2000	100	21
	300			15
	400			8
	500			4
[21]	200	2000	100	21
	300			15
	400			8
	500			4

5 Conclusions and Future Work

This research has presented a comprehensive numerical investigation into the influence of key working conditions (i.e., the capacitor bank capacity, discharge energy, and coil length) on the plastic deformation of tubular workpieces in electromagnetic tube expansion. Using a coupled finite element model, the effects of these parameters on magnetic force and tube deformation were systematically analyzed. The findings demonstrate that an increase in capacitor bank capacity or discharge energy leads to a significant rise in the magnetic force, which in turn enhances the deformation of the tube. Additionally, the length of the coil plays a critical role in determining the deformation pattern, with variations in coil dimensions affecting the uniformity and magnitude of the expansion. These results emphasize the importance of optimizing the forming apparatus parameters to achieve desired deformation characteristics.

Future research will focus on refining the numerical model to account for more complex material behaviors, such as strain rate sensitivity and thermal effects, which can further enhance the accuracy of the simulations. As well as exploring other emerging forming trends (e.g., [22-30]).

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

I. Boutana: Conceptualization, Methodology, Formal Analysis, Writing—Original Draft, Writing—Review and Editing. **M.R. Mekideche**: Methodology, Formal Analysis, Writing—Review and Editing.

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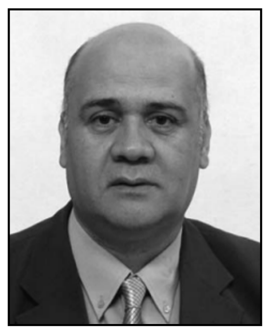
Biographies

Ilhem Boutana is currently an Associate Professor in Electrical Engineering at the University of Jijel, Jijel, Algeria. In 1992, she received her first diploma as an Electrical Engineer from the University of Bejaia, Algeria. From 1993 to 1996, she was an assistant and post-graduate student preparing her magister, and she received her Ph.D. degree in 2008 from University of Jijel, Algeria. Also, she was the head of the Electrical Engineering department from 2003 to 2019. She has supervised more than 40 engineers and master's students. She is author and co-author of more than 50 articles in international conferences and Journals. Her current research interests include covering several aspects related to numerical modeling with finite element methods, electromagnetic forming, and electrohydraulic forming.



Mohamed Rachid Mekideche is currently a Professor in Electrical Engineering at the University of Jijel, Jijel, Algeria. In 1981, he received her first diploma as an Electrical Engineer from University of Science and Technology, Oran, Algeria. He received his magister degree from the National Polytechnic School, Algiers, Algeria, in 1986 and his Ph.D. degree from the University of Nantes, Nantes, France, in 1993. Since 1996, he has been with the University of Jijel, Algeria, where he is currently the Dean of the Faculty of Science and Technology. He has supervised more than 100 engineers, master and PhD's students. He is author and co-author of more than 100 articles in international conferences and Journals.