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Advancing Sheet Metal Formability: An In-Depth Numerical Investigation and Enhanced Modeling of Electrohydraulic Process

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Abstract **-** *Electrohydraulic Forming* (EHF) is a cutting-edge manufacturing technique that utilizes high-voltage capacitor discharges within a liquid-filled chamber to efficiently shape sheet metals. By generating a pulsed pressure wave from electrical discharge, EHF achieves rapid plastic deformation, offering significant advantages in precision and versatility. This paper presents an innovative numerical model developed using *COMSOL Multiphysics* to study the EHF process, incorporating the *Johnson-Cook model* to simulate plastic deformation. A detailed analysis of formability is conducted for various materials, with a focus on *aluminum*, *copper*, and *steel*, under different operating conditions. Results highlight the significant influence of *material properties*, *electrode-to-workpiece distance*, and *applied pressure* on deformation outcomes. Aluminum emerges as the most promising material for EHF due to its superior formability.

Keywords**:** Electrohydraulic Forming, Finite Element Method, High-Speed Forming, COMSOL Multiphysics, Material Formability.

1. Introduction

Nowadays, a range of *high-speed forming* methods, such as *Electromagnetic*, *Explosive,* and *Electrohydraulic Forming* (EHF), have been recently proposed and investigated in the active literature (e.g., [1-4]). The superiority of high-speed forming lies in its *enhanced formability*, attributed to the high pressure and high-speed characteristics when compared to conventional static forming processes. In fact, during the EHF process velocities exceeding $100\ m/s$ are achieved within a few microseconds. Therefore, material deformation occurs at extremely high strain rates, associated with dynamic effects. This latter leads to a notable increase in forming limits compared to those observed under *quasi-static loading* (e.g., [5]).

Indeed, EHF represents a high-velocity forming method designed for sheet materials, this method was preliminarily studied between 1950 and 1970 [6]. In the EHF process, the sheet is positioned as a wall within a chamber filled with water or another liquid, which sets the stage for a dynamic interplay of forces. Inside the liquid chamber, two electrodes are strategically placed and connected to a *capacitor pack*, a pivotal component in the process. This configuration generates an electric spark, creating pressure through the liquid to enable the sheet to be deformed freely or conform to a die, assuming a predetermined shape with precision and speed (see Figure 1).

Moreover, the EHF process holds diverse applications across industries (e.g., [7-8]). In automotive manufacturing, EHF is employed for shaping sheet metal components like body panels and enhancing production efficiency. The aerospace sector benefits from EHF ability to rapidly and precisely form lightweight materials for aircraft components, contributing to aerodynamic efficiency. Also, in medical device manufacturing, EHF aids in producing precision components such as implants. Furthermore, the process is well-suited for prototyping and small-batch production scenarios, where quick tooling changes and short production runs are essential.

Following these considerations, in this paper, we propose an innovative numerical model that aims to *investigate and Characterize the process of sheet metal forming based on the Electrohydraulic Forming method*. In fact, our contributions pave the way for the interesting research area of emerging high-speed forming methods by investigating the electrohydraulic forming process. Moreover, this research is an extension of our previous short paper [9], where we presented a brief introduction to our EHF approach for sheet metal forming. Specifically, we make the following contributions, (*i*) we initiate by presenting a comprehensive overview of the context, state-of-the-art analysis, and motivation that inspired us to conduct this research. (*ii*) we illustrate the fundamental principle of the electrohydraulic process, as well as introduce the essential mathematical models and the geometry and parameters of our numerical investigation. (*iii*) we conduct a rigorous numerical assessment and analysis of the effect and impact of the electrical discharge and consequently, the high pressure that allows the plastic deformation of the metal sheet, in order to ensure the effectiveness and reliability of the proposed numerical model. (*iv*) we also, evaluate the effect of material characteristics on the sheet deformation, its dome height, and its final shape under electro-hydraulic pressure.

The remaining part of this paper is organized as follows. Section 2 focuses the attention on presenting some relevant related work to our research. In Section 3, we present the mathematical models as well as describe the principles of the electrohydraulic process. After that, in Section 4, we report our extensive applications and the results obtained. Finally, Section 5 contains conclusions and possible future works.

2. State-Of-The-Art Analysis

In this Section, we highlight some of the most relevant and pertinent related work that appeared in the active literature in the context of high-speed forming methods specifically, electrohydraulic forming.

The authors of [10] investigate the effect and influence of *energy pulse duration* on electro-hydroforming processes. Various RLC-type topologies were employed to modify the discharge regime, spanning from underdamped to overdamped systems, thereby manipulating the arc duration. The investigation establishes a direct correlation between arc duration and the efficacy of the forming operation, evidenced by fluctuations in measured height. Beyond empirical observations, this study contributes to the enhancement of our comprehension of the electrohydraulic forming process, offering valuable insights for the optimization of process parameters.

However, *Ali et al.* [11] delve into an in-depth examination of the EHF process, focusing specifically on the influence of bridge wire material and its diameter on efficiency. Their investigation involved a meticulous comparison of the formability, specifically dome height, and strain distribution of *AA 5754 sheets*. To achieve this, the study employed bridge wires made of Aluminum and Copper, each with three distinct diameters. In addition to experimental work, the researchers advanced their understanding through the development of an alternative Finite Element Method model for EHF. Leveraging the capabilities of LSDYNA software, this model simulated the explosive process based on TNT explosives, providing a comprehensive computational perspective to complement the empirical findings. This multifaceted approach not only enhances our comprehension of the EHF process but also contributes to the refinement of numerical modeling techniques in this dynamic field of study.

[12] introduces a simplified design methodology for Electrohydraulic forming processes. The primary objective is to outline a cost-effective preform concept, especially in scenarios where the extended formability of the EHF process falls short of achieving the desired shape. This conceptual approach serves as an innovative solution, representing a pivotal advancement that facilitates the utilization of higher-strength, lighter, and less formable materials within the automotive industry. By proposing this novel concept, the study not only addresses limitations in the existing formability of EHF processes but also positions itself as a progressive stride toward enabling the incorporation of advanced materials, aligning with the ongoing pursuit of lightweight and high-strength materials in automotive manufacturing.

Moreover, [13] explores the formability testing of dual-phase Steels in EHF conditions. By rapidly discharging stored electrical energy across submerged electrodes, EHF converts electrical energy into kinetic energy for sheet metal forming. The study not only reports experimental results but also introduces a modeling technique to analyze and simulate the EHF process. Comparison with quasi-static testing reveals significantly higher strains achievable in EHF, particularly in the contact area between the blank and the die.

3. Numerical Modeling of Electrohydraulic Forming Process

In this Section, we introduce the essential mathematical models for investigating the problem of sheet metal forming using the EHF method, as well as presenting its fundamental principles.

3.1. Fundamental Principles of EHF

The basic principles of the electrohydraulic forming device as shown in Figure 1, center upon the conversion of electrical energy into mechanical energy via a discharge between the two electrodes immersed in either water or oil. The arc discharge causes the surrounding fluid to be rapidly vaporized, resulting in a substantial increase in pressure within the fluid. This elevated pressure pushes the sheet material into a die, facilitating either the formation of a specific shape or free deformation. The necessary energy for this discharge is stored in a large capacitor bank.

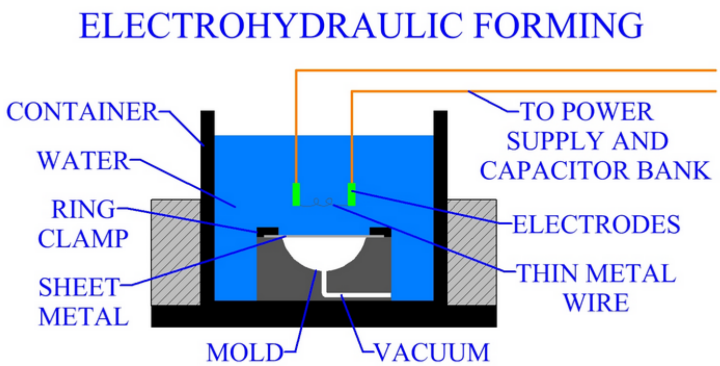


Fig. 1: Schematic View of Electrohydraulic Forming System.

This process offers significant benefits to various industries by allowing the *cost-effective* and *time-efficient* production of intricate parts with complex shapes. Although EHF advantages such as enhanced control over the pressure pulse as an energy source and suitability for small to medium-sized workpieces, it remains a process demanding comprehensive research to better understand the complex and interlinked physical mechanisms.

3.2. Theoretical Analysis and Mathematical Models

The purpose of our approach is to create a simple and exact model that could simulate the electrohydraulic pulse forming of a plate. Indeed, we choose to construct a finite element model that combines the *hydraulic* and *mechanical* problems involved in this process.

Equation (1), often known as *Newton's second law*, is the fundamental equation that governs the plastic deformation of any isotropic material.

$$\rho\frac{\partial^2\vec{u}}{\partial t^2} - \nabla.[\sigma] = \vec{F} \tag{1}$$

where u is the displacement field, σ represents the stress tensor. F is the load vector and ρ is the density.

In 2D, the deformation ε is completely defined by the displacement components *(u,v)* and their derived (see Equation (2)). It is formed by three components, as presented in Equation (3).

$$\varepsilon_x = \frac{\delta u}{\delta x},\ \varepsilon_y = \frac{\delta u}{\delta y},\ \varepsilon_{xy} = \varepsilon_{yx} = \frac{1}{2}\left(\frac{\delta u}{\delta y} + \frac{\delta u}{\delta x}\right) \tag{2}$$

with:

$$\varepsilon = \varepsilon_{el} + \varepsilon_{th} + \varepsilon_p \tag{3}$$

such that ε_{el}, ε_{th}, ε_p represent the elastic deformation, thermal deformation, and plastic deformation, respectively.

For what concerns the mechanical behavior of materials, we used the *Stress-Strain relationship* for elastic deformation, as shown in Equation (4).

$$\sigma = D\varepsilon_{el} + \sigma_0 \tag{4}$$

with:

$$D^{-1} = \frac{1}{E}\begin{bmatrix} 1 & -v & -v & 0 & 0 & 0 \\ -v & 1 & -v & 0 & 0 & 0 \\ -v & -v & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2(1+v) & 0 & 0 \\ 0 & 0 & 0 & 0 & 2(1+v) & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(1+v) \end{bmatrix} \tag{5}$$

Moreover, the equations that govern the movement of any fluid are the equation of conservation of the quantity of motion and the mass conservation one, presented in Equation (6).

$$\begin{cases} \rho\left(\vec{V}.\vec{grad}\right)\vec{V} = \vec{F} - \vec{grad}\,\mathrm{P} + \eta\,\Delta\,\vec{V} + \frac{1}{3}\eta\vec{grad}\left(div\vec{V}\right) \\ \mathrm{div}\,\vec{V} = 0 \end{cases} \tag{6}$$

On the other hand, when addressing the plastic deformation of the sheet, our approach involved the utilization of the *Johnson-Cook model* presented in Equation (7). This model, widely recognized in materials science and engineering, provides a robust framework for characterizing the behavior of materials subjected to plastic deformation under varying conditions.

$$\sigma = \left(A + B.\varepsilon^{n}\right).\left(1 + C.ln\left(\frac{\varepsilon}{\varepsilon_0}\right)^{p}\right).(1 - \left(\frac{T - T_0}{T_m - T_0}\right)^{m}) \tag{7}$$

with σ representing the strain rate, ε_0 represents a reference strain rate, A, B, n, p, and m are *Johnson-Cook* parameters, T_m is the melting point of the material, and T_0 is the surrounding temperature.

Nevertheless, it is worth noting that in our modeling approach, the *thermic deformation* has not been taken into consideration. Furthermore, it is noteworthy that Numerical modeling is crucial for designing any technological process (e.g., [1-4]) since experimental assessment of EHF can be costly and hard to perform. In this work, a finite element model was carried out to investigate the possibility of doing simulations of the EHF technique. The software used for the simulation is COMSOL MULTIPHYSICS. The simulations were qualitatively validated through the dome height of the EHF experiment, performed by *Melander et al.* [14]. Another investigation consists of analyzing and comparing the formability of different materials under the EHF process.

4. Results and Discussion

In this Section, we present our extensive numerical evaluation and assessment conducted to analyze the process of sheet metal forming using the EHF method. In order to better understand the mechanism of deformation and forming mechanisms within EHF processes, numerical modeling is conducted.

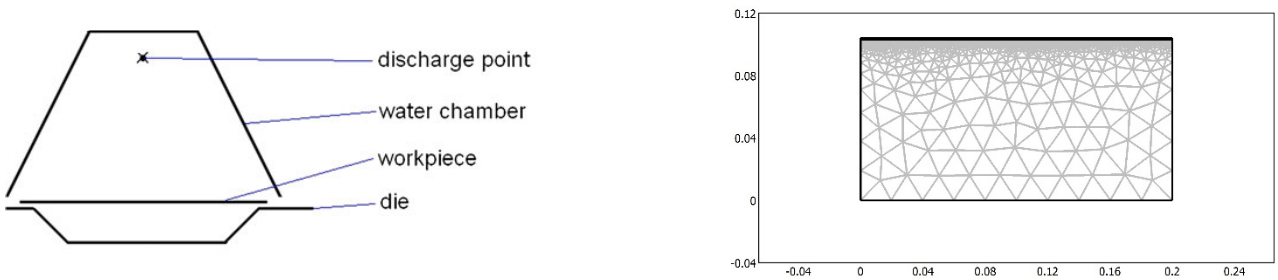
The EHF simulation model employed in this study encapsulates the effect of an electrical discharge at the electrode level as a pressure generated at the central point of the liquid chamber. The energy from the electrical discharge is intended to transform into static pressure within the water, calculated as the ratio of electrical energy to liquid volume. Under this assumption, the kinetic impact is considered negligible [14]. The focus of our applications involved the exploration of free EHF, without the use of a die. Furthermore, we conducted a comparative analysis of the mechanical behavior and formability of various materials, thereby contributing to a comprehensive understanding of the diverse responses observed in the EHF process. The mechanical characteristics of the sheets under investigation are detailed in Table 1.

Table 1: Physical Properties.

Material	Young Module	Poisson Coefficient	Density
Aluminum	70.10^9	0.33	2700
Copper	110.10^9	0.35	8700
Steel	200.10^9	0.33	7850

4.1. Electrohydroforming of Aluminum Plates

Our initial investigations involve both practical trials and simulations focused on EHF without the implementation of a die, commonly referred to as *free forming*. In this configuration, the sheet is allowed to expand freely into a vacuum cavity. The schematic representation of the experimental setup, comprising the water chamber, die, and sheet, is depicted in Figure 2(*a*), which corresponds to the experimental setup used in [14]. The water chamber designated for EHF measures 200 mm in width and 103 mm in depth, with the central electrodes positioned 50 mm above the base of the chamber.



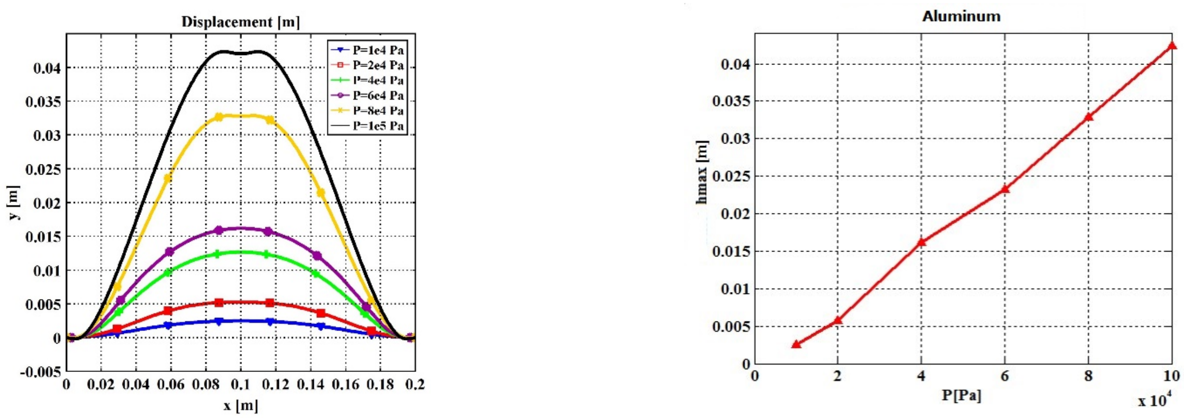
(*a*) (*b*)

Fig. 2: Schematic View of Experimental Setup [14] (*a*) – System Finite Element Mesh (*b*).

The simulated sheet, illustrated in Figure 2(*b*), has a diameter of 200 mm and a thickness of 1 mm. For the simulation, the sheet is modeled using a *COMSOL mesh*, consisting of 23,022 triangular elements and 12,037 nodes, as demonstrated in Figure 2(*b*).

Moreover, we conducted a numerical assessment of the shapes achieved by Aluminum plates, as illustrated in Figure 3(*a*), considering various pressure values at the discharge point ($P = 10^4 - 10^5$ Pa). These results indicate that the electrical pressure at the discharge point notably influences the deformation of the plates. Specifically, an increase in electrical pressure exacerbates the tendency for the plates to experience clogging. In fact, Figure 3(*a*) depicts various forms of EHF plates generated under various pressures. On the other hand, when the pressure is high, the maximum displacement of Aluminum plates is more essential. Figure 3(*b*) shows the dome high of the deformed sheet with respect to the applied pressure.

As shown in Figure 3(*b*), the maximum displacement of Aluminum plates is nearly proportional to the pressure under consideration. Which highlights the relationship between the applied electrical pressure and the resulting forms of the Aluminum plates. These findings are comparable to those reported experimentally by *Melander et al.* [14].



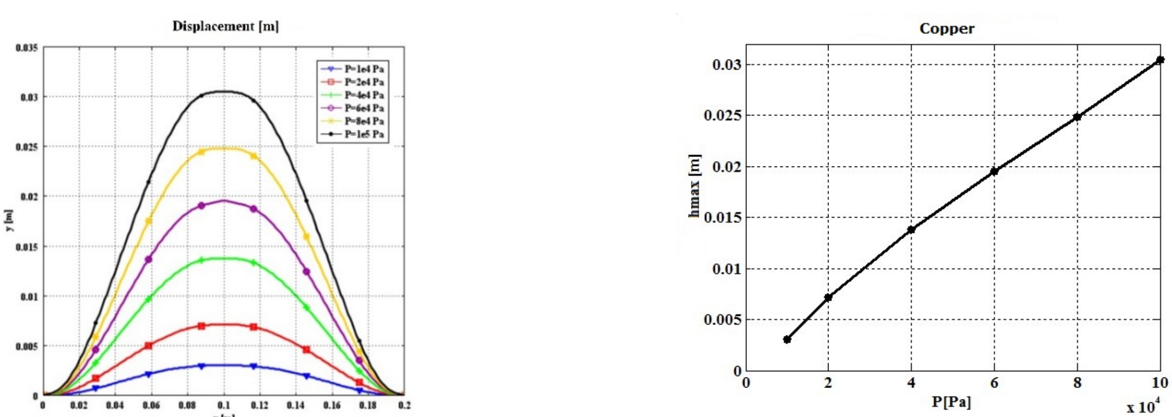
(*a*) (*b*)

Fig. 3: Aluminum Plate Deformation with Different Pressure (*a*) – Maximum Displacement of the Aluminum Plate according to the Applied Pressure (*b*).

4.2. Comparison of the Formability of Different Materials under Free Electrohydroforming

In order to comprehensively assess the formability of several materials under EHF conditions, we expanded our investigation beyond Aluminum plates. Our assessment incorporated plates composed of a range of materials, notably including *Copper* and *Steel*, (see Table 1).

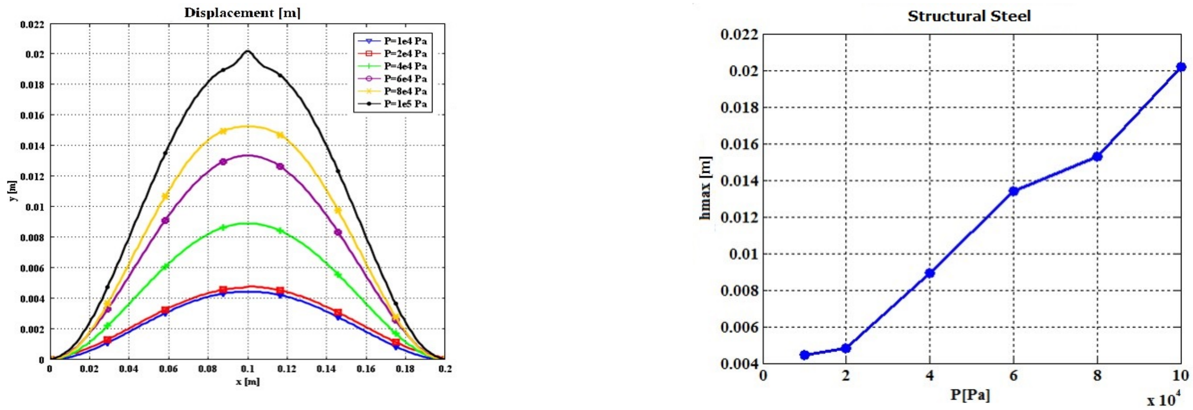
This comprehensive analysis of the formability characteristics across multiple metal types enhances our understanding of the versatility and applicability of EHF across various material compositions. Upon examining the deformation of Copper plates subjected to different electrohydraulic pressures, as depicted in Figure 4(*a*), it becomes evident that Copper exhibits lower formability compared to Aluminum. Furthermore, the maximum displacement of Copper plates is directly correlated with the applied pressure, as illustrated in Figure 4(*b*). This correlation highlights the sensitivity of Copper to variations in applied pressure during the electrohydraulic forming process.



(*a*) (*b*)

Fig. 4: Copper Plate Deformation with Different Pressure (*a*) – Maximum Displacement of the Copper Plate according to the Applied Pressure (*b*).

Nonetheless, as illustrated in Figure 5(*a*), it becomes apparent that structural Steel exhibits the lowest formability when subjected to EHF. The variability in maximum displacement at the plate level, influenced by applied pressure, is not consistent across the range (see Figure 5(*b*)).



(*a*) (*b*)

Fig. 5: Steel Plate Deformation with Different Pressure (*a*) – Maximum Displacement of the Steel Plate according to the Applied Pressure (*b*).

This behavior signifies that Steel responds uniquely under EHF conditions, prompting further investigation into the distinctive characteristics governing the formability of Structural Steel in comparison to other materials. This comparative study led to the conclusion that Aluminum is the material that has the best formability under EHF. Furthermore, we can note that the three shapes obtained, under the same pressure $P = 10^5\ Pa$, are distinct, as shown in Figure 6.

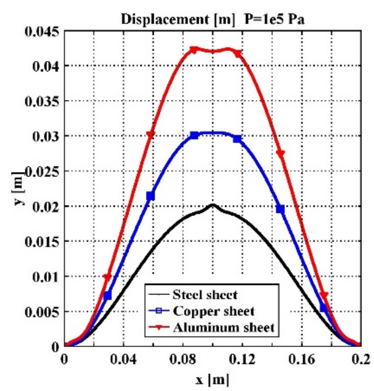


Fig. 6: Different Plates Deformation at $P = 10^5\ Pa$.

The numerical results align well with experimental findings, highlighting the following key points: (*i*) The EHF Process is suitable for forming both conductive and non-conductive metal sheets and tubes. (*ii*) Aluminum is the most promising material for EHF due to its superior formability and mechanical response under electrical discharge pressure. (*iii*) The physical properties significantly influence the deformation rate of metal plates. (*iv*) Electrode-to-Workpiece Distance is a crucial parameter in the deformation process. (*v*) The forming generator's energy, which determines applied pressure, is a key factor. (*vi*) EHF achieves higher effective plastic deformation levels compared to processes like electromagnetic forming.

5. Conclusions and Future Work

In this paper, we present and deeply assess a numerical model for sheet metal forming using the EHF process. Moreover, we present the numerical results obtained for EHF applications using three different materials. The EHF simulation model describes the effect of electrical discharge at the electrode level as a pressure generated at the middle point of the electrodes. In addition, a comparison of mechanical behavior and formability of different materials is discussed. In future work, we plan to conduct in-depth investigations on many aspects of the process, including electrical shock waves in the EHF medium and also developing a 3D model to deal with the complex geometries of industrial applications, as well as investigating other *emerging forming trends* (e.g., [15,16]).

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