3D modelling of the mechanical behaviour of magnetic forming systems

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ABSTRACT

High-speed forming methods become attractive in manufacturing and significantly reduce the cost and energy requirements. Electromagnetic forming is a high-velocity pulse forming technique that applies electromagnetic forces to sheet or tubular workpieces using a pulsed magnetic field. In order to understand the physical behaviours of materials, numerical modeling is highly desired. Therefore, in this study, we investigate the mechanical behaviour of the electromagnetic sheet stamping and magnetic tube expansion and compression systems. For these 3D simulations, COMSOL multiphysics software is used. It provides the possibility to model the electromagnetic aspects of the problem along with the thermal and mechanical aspects in a coupled method. The developed 3D numerical fully coupled models lead to analyze the transient magnetic fields, Lorentz forces acting on workpieces, and the plastic deformations obtained in several magnetic forming systems. The effects of systems parameters are also investigated such as the coil's form and the number of its turns.

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1. INTRODUCTION

The electromagnetic forming (EMF) process is a high-velocity metal forming process, based on the application of high electromagnetic (EM) energy during a very short time, to obtain the desired deformation. The application of magnetic force is then, contact-free. EMF process consists of a fast discharge of a high pulsed current in a coil, inducing strong Lorentz forces in workpieces to be formed. This process is one of many other high-speed forming processes such as explosive forming or electrohydraulic forming. When compared to these technologies, the EMF can be adapted to different geometries and various sizes. It is more suitable for mass production, for production rate, cost, and safety reasons. The most requirements for EMF are to analyze the evolution of forming operation and the forming parameters to achieve high-quality forms, particularly in complex geometries. These requirements motivated our developments presented in this paper, based on 3-dimension (3D) modeling. For this purpose, 3D multi-physical simulations are performed with COMSOL multiphysics code.

Oliveira *et al.* [1] performed experimentation and modelisation on an Aluminium alloy sheet free-formed by the EMF method. They showed that EMF can improve the poor formability of Aluminum alloys and proved that this technique can be successful in aerospace and automotive industries due to the extensive use of Aluminium alloys. For others, metallic materials, Andersson and Syk [2] studied experimentally the EMF of carbon steel workpieces, whereas Li *et al.* [3], worked on EMF titanium alloy sheets. They found that the frequency of the current through the forming coil must increase to create the same forming properties as for Aluminium. So, the energy required, to deform materials with low conductivity, is higher than the one in the case of materials with high conductivity.

Simulation of the EMF process is very important to understand this process. Various simulation approaches have been applied to simulate this technology and provided a considerable prediction of workpiece deformation. Indeed, in Bartels *et al.* [4], Two EMF simulation models for tubular workpieces were investigated and compared: uncoupled model with sequential coupling method, using ANSYS software and it has been confirmed that the most accuracy is obtained by the coupled model. However, Kumar and Nabi [5] simulated metal sheet EMF in a full coupled electromagnetic-structural model. Where Joseph *et al.* [6] developed numerical model, based on finite element method for Aluminium sheet EMF, using commercial software ANSYS/EMAG. All these previous analyses were carried out considering the problem as axisymmetric.

In the work of Kim *et al.* [7], carried out using LS-DYNA, the influence of coil geometry on aluminum alloy tubes forming was investigated, they conclude that tube expansion can be significantly increased. Qiu *et al.* [8] developed an EMF technique, using COMSOL software, proposing a new EMF method based on driven rings. This technique allows enhancing the forming process, by placing conducting rings, between the coil and the workpiece. They showed that the distribution profile of EM force can be controlled by the rings' parameters. So, they improved the performance of the EMF process and show that this method can be widely implemented in industrial applications.

Qiu *et al.* [9], they investigated the EM tube expansion with concave and helix coils. Simulation and experimental analyses have been conducted, by these authors, to explore the homogeneity of tube deformation under these two coils. The proposed concave coil is expected to reinforce the EM force distribution profile and hence improve the axial homogeneous deformation of the tube. To resolve the tube EM bulging simulation with a field shaper, Qiu *et al.* [10] have also proposed a simplified two-dimension (2D) model, based on the distribution of the current induced in the field shaper. Their 2D simulation model, using a field shaper, analyzes the tube EM bulging performance. Solving the radial deformation problem, Li Qiu *et al.* [11] proposed an EMF technique, with a field shaper. They improved the uniformity of sheet EMF.

Laie *et al.* [12] developed a coupled analysis model for the commonly used EM actuator DC coil, which takes into account the interaction between the EM and mechanical fields, and takes into account the effects of geometry and material parameters, thereby improving the accuracy of the analysis. Furthermore, they proposed a criterion for judging the applicability of the basic assumption made on the analytical model that the EM field induced by the coil can be completely confined by the workpiece. This proposed analytical model provides important design assistance. However, in another work, Lai *et al.* [13] developed an analytical method to optimize the coil geometry in EMF. It has been found that constant voltage coils have optimal channel heights that can be analytically represented by the coil geometry. Previous studies of EMF processes using dies have assumed that the dies are non-conductive. However, for the cases with a conductive die, the EM forces acting on the workpiece can significantly change, because eddy currents would also be induced in the die. Cao *et al.* work [14], a numerical model is proposed, coupling the finite element method, and circuit simulation approach, using ANSYS, for analyzing the workpiece deformation. They have explored how the eddy current in a conductive die affects the EMF process.

Ouyang *et al.* [15] developed an EMF method in a dual-coil configuration that exploits the attractive force between the tube and the coil for tube volume reduction. This method can utilize two separate capacitor banks, with outer and inner coils to adjust the magnetic field and eddy currents inside the tube. According to numerical and experimental results they have found that the inner and outer coils have an optimal discharge voltage for achieving the maximum deformation. They have also demonstrated numerically and experimentally [16], the effectiveness of the Aluminum alloy plate EMF process using a low-frequency discharge. They have analyzed in detail two factors for an attractive forming process include Lorentz force properties and sheet metal deformation. Xu1 *et al.* [17] developed an EM expansion method using a dual-coil EM. They also analyzed the effect of the system parameters and the residual stress. They showed the effectiveness of the used method.

The EMF process is particularly used in the aerospace and automotive industries to form and join metal sheets and tubes. The geometry of the pressure coil has a significant effect on the performance of the system. Soni *et al.* [18] performed the finite element modeling (FEM) analysis of tube deformation, using LS-Dyna software. They studied the influence of coil shape on the deformation and the correlation of finite element calculation parameters with experimental results. Shrivastava *et al.* [19] studied tube compression and the effect of process parameters. Their work contains experimental and finite element analysis of tube compression using a bitter coil without a field shaper and their validation depicts the correlation of the process parameters like energy, gap, and the number of banks with tube deformation.

The Lorentz forces are induced in the workpiece by eddy currents, so the coils used, in EMF processes should be specially conceived. Zeng *et al.* [20] investigated numerically an EMF method, with inverse current instead of induced eddy currents. This method was validated, numerically and experimentaly for the 5754 aluminum alloy strip. The effective technology to join dissimilar materials tubes is EMF. Liu *et al*. [21] proposed a new approach for EM tube joining using a flat coil. for the manufacturing of torque joints. They show that in this way, it becomes more convenient and flexible for the industrial application of EM crimping, and only one tool coil is enough to be used for tubes with various diameters.

Patel and Nagrale [22] performed experiments on the EMF of copper workpieces and described it using optical microscopy. In this work, a finite element model is considered and analyses the deformed copper material. Their results demonstrated that the improvement of copper mechanical properties was allowed by the increase of the strain rate. From the microstructures of the deformed copper sample, they inferred that fine grain structure in copper is induced by EMF plastic deformation

The manufacturing process of 2219 aluminum alloy (AA2219) thin-walled parts nowadays exhibits challenges to meet the service requirements of the high-performance and lightweight new-generation launch vehicle. Xie *et al*. [23] employed different aging treatments and subsequent EMF to investigate the microstructure evolution and mechanical properties of AA2219. They have investigated the morphology, size, and distribution of the precipitated phase. Their work provided guidance for the strengthening treatment and forming process of AA2219 high-performance parts.

Weight reduction is especially important in the automotive and aerospace industries. This results in lower fuel consumption and high efficiency. Therefore, a numerical model must be developed to predict the changes in the discharge circuit, the corresponding radial pressure, and the stress acting on the tube. Tiwari N *et al*. [24] performed the EMF simulation on an Aluminum tube, with a helical copper coil. They developed a coupled 2D simulation model using the COMSOL software, to predict the maximum deformation during the EMF process, and the workpiece hardness. Until now, the numerical models dealing with EMF technology are mostly in 2D, considering particularly axisymmetric systems. So, 3D models are highly needed to simulate complex geometries of industrial parts.

In this study, 3D simulations by finite element analysis Software COMSOL multiphysics are developed to calculate the eddy currents, the magnetic forces distributions, applied on the work-pieces, and the deformation of the workpiece occurring during the impulse EMF process, these 3D simulations are fully coupled, to well investigate the behavior of metal sheets and tubes under EMF. This is indispensable for an effective process design of real industrial applications. Depending on the arrangement and the geometry of the coil and workpiece, several applications of EMF are achieved: flat metal sheet bulging as well as compression and expansion of tubular pieces. Other applications, simulated par our 3D models, are plates and tubes joining by the EMF process.

2. PHYSICS OF THE PROCESS

In the EMF process, a transient EM field is produced in the coil, when the capacitor discharges. It induces eddy currents over the adjacent workpiece and important EM forces are generated between the coil and the conductive workpiece material. It can shape it freely (free-forming) or with the help of a die. Figure 1 shows the principle of EMF and indicates different applications of EMF: compression (Figure 1(a)) and expansion of metal tubes (Figure 1(b)) and bulging of flat sheets (Figure 1(c)) [25].

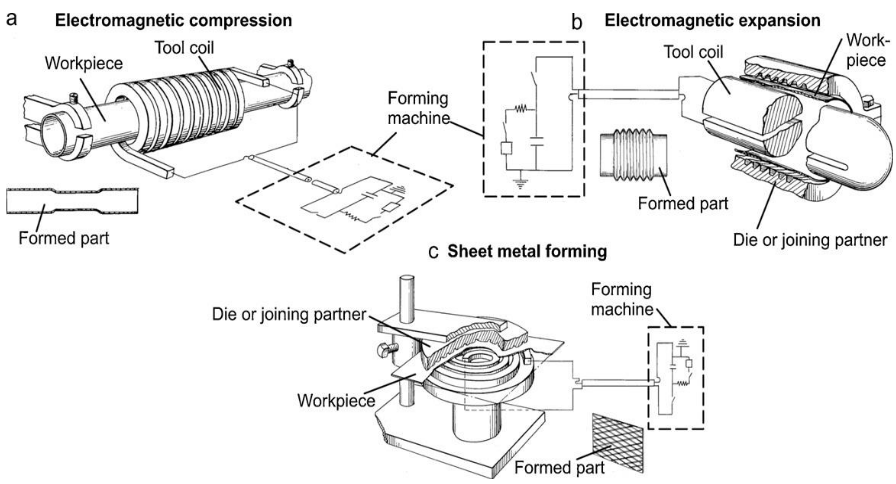

Figure 1. Different types of EMF setup [25], (a) tube compression, (b) tube expansion, (c) bulging of flat sheets

2.1. The electromagnetic model

The EM fields are governed by Maxwell equations. The magnetic vector potential formulation (1) leads to the knowledge of the distribution in time and space of the magnetic field and induced currents.

$$\sigma \frac{\partial \vec{A}}{\partial t} + \nabla \times \left(\frac{1}{\mu} . \nabla \times \vec{A} \right) - \sigma . \vec{v} \left(\nabla \times \vec{A} \right) = \overrightarrow{J_{ex}} \tag{1}$$

Where μ is the magnetic permeability, σ the electrical conductivity and J_{ex} the external current density. Lorentz force F on the workpiece can be determined as:

$$\vec{F} = \overrightarrow{J_{ind}} \wedge \vec{B} = \overrightarrow{J_{ind}} \wedge \left(\nabla \times \vec{A} \right) \tag{2}$$

The discharge current could be obtained (4), by Solving the differential in (3).

$$\frac{d^2 I(t)}{dt^2} + 2\xi\omega \frac{dI(t)}{dt} + \omega^2 I(t) = 0 \tag{3}$$

$$I(t) = V_0 \sqrt{\frac{C}{L}} e^{-\xi\omega t} \sin \omega t \tag{4}$$

Where L, R are the system inductance and resistance respectively, ω is the angular frequency, and ξ the damping term, given by: $\xi = \frac{1}{2} R \sqrt{\frac{C}{L}}$.

2.2. The solid mechanics model

The workpiece deformation occurring during EMF is obtained by the equilibrium equation:

$$\rho \frac{(\partial^2 \vec{u})}{\partial t^2} + \nabla \cdot \vec{\sigma} = \vec{F} \tag{5}$$

Where σ is the workpiece stress, F is the EM forces, ρ is the material density, and u is the displacement vector.

3. RESULTS AND DISCUSSION

3D finite element, fully coupled models were performed using COMSOL multiphysics software, to analyze the workpiece's free deformations during EMF processes: plate stamping, tube expansion, and compression. Plates assembly and tube joining are also investigated.

3.1. Plates stamping

The simulated 3D plate stamping system is shown in Figure 2, whilst its basic properties are given in Table 1. It includes a copper coil of 5 turns below a 0.5 mm aluminum plate attached to its periphery to prevent its displacement. The discharging current applied to the plate stamping system is shown in Figure 3. The different deformations of the plate, with different coils (3, 5, 7, and 9 turns), shown in Figure 4, are obtained at 50 µs. We can note that the deformation of the plate is all the more important as the number of turns is large. This result is theoretically confirmed. In addition, different forms are obtained in each case (Figures 4-5).

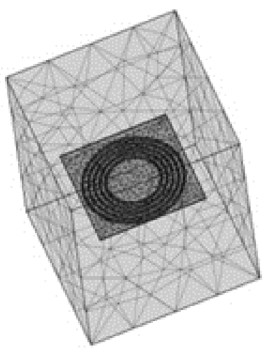

Figure 2. Plate stamping system

Table 1. System parameters

Coil electrical conductivity (Copper) [s/m]	Plate electrical conductivity (Aluminum) [s/m]	Aluminum density [kg/m^3]	Aluminum Young's modulus [Pa]	Aluminum Poisson's ratio
5,998.10^7	3.774. 10^7	2700	70.10^9	0.33

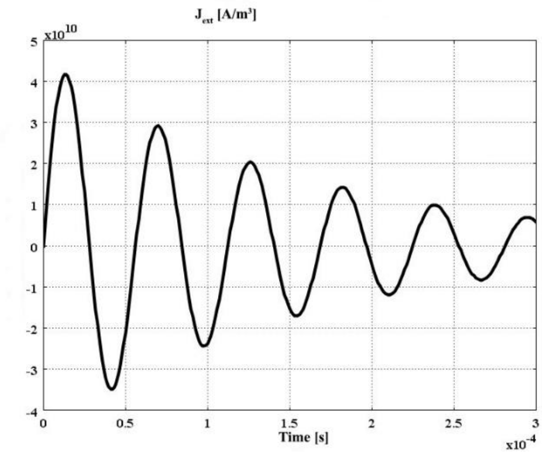

Figure 3. Discharge current

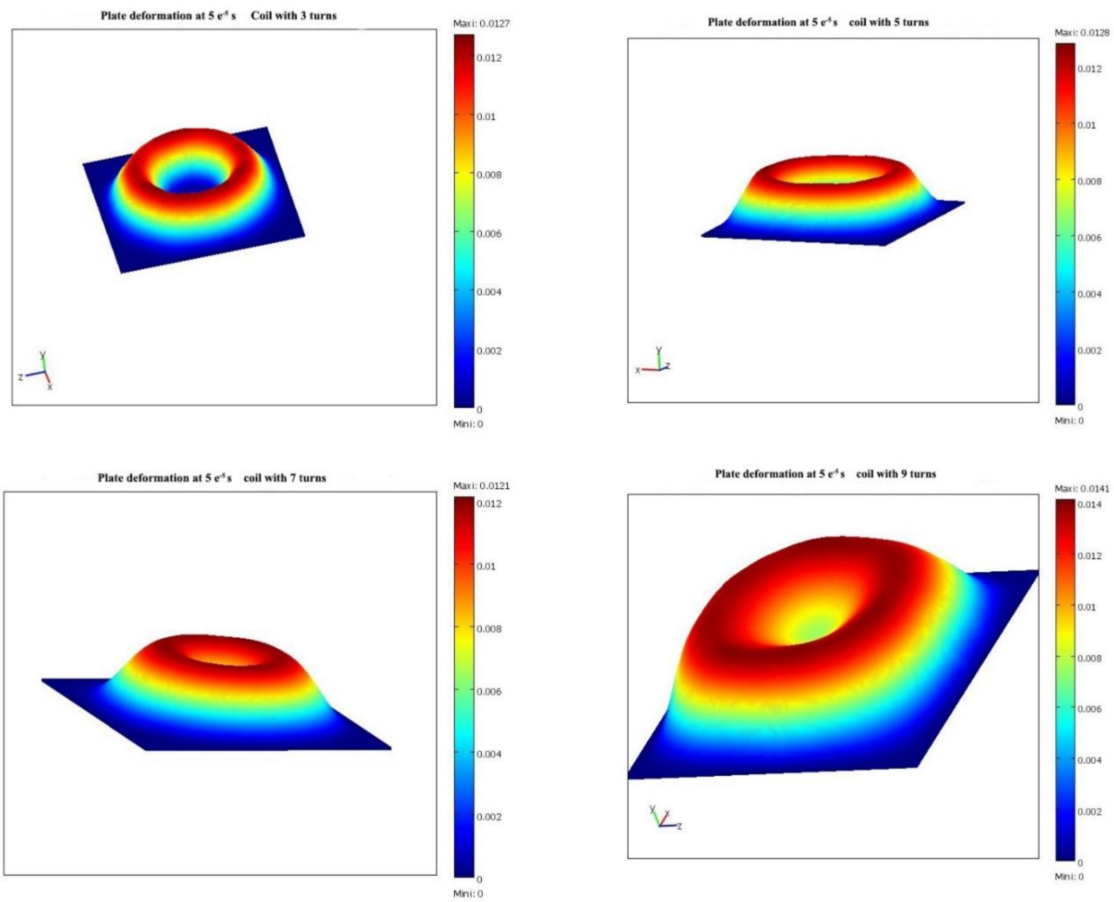

Figure 4. Plate stamping with different coils

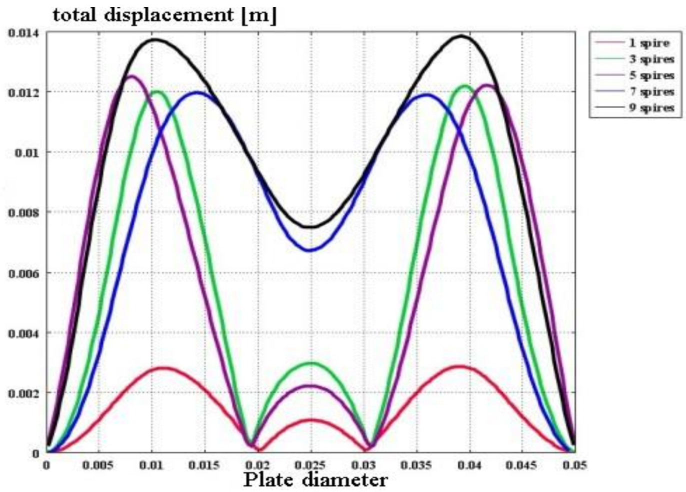

Figure 5. Displacements of the plates with different coils

3.2. Tubes expansion and compression

Other numerical studies are on tube forming systems: Tube Expansion (Figure 6) and tube compression (Figure 7). The tube expansion system includes a copper coil with 5 turns, concentric inside of an aluminum tube. With the same magnetic forming energy, different shapes are obtained (Figure 8), with different coils (2-3-5-7 turns). In the case of tube compression, the coils (with 1 turn, 3, and 5 turns) are outside the tubes, providing different forms for compressed tubes (Figure 9).

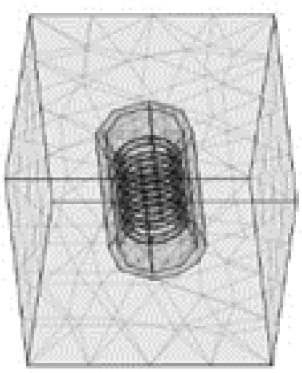

Figure 6. Tube expansion system

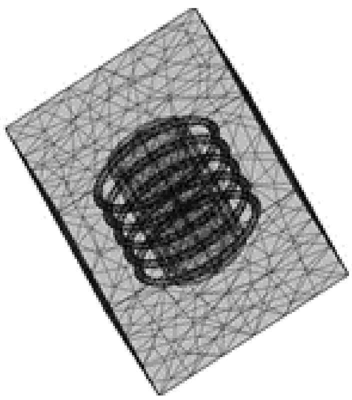

Figure 7. Tube compression system

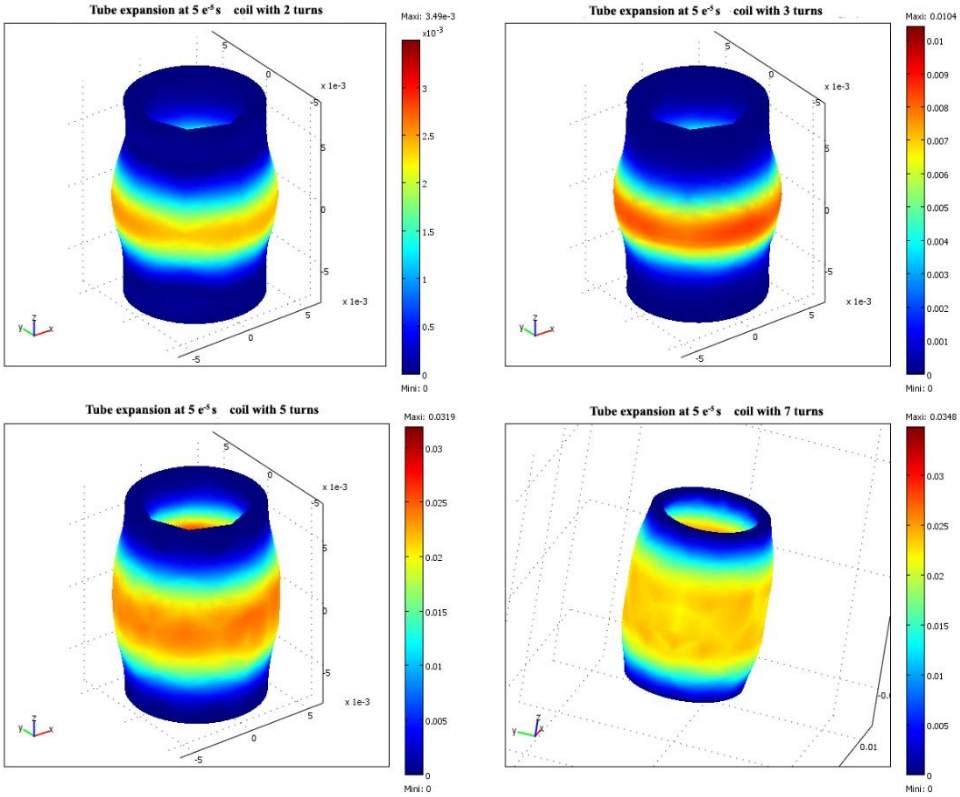

Figure 8. Tubes expansion with different coils

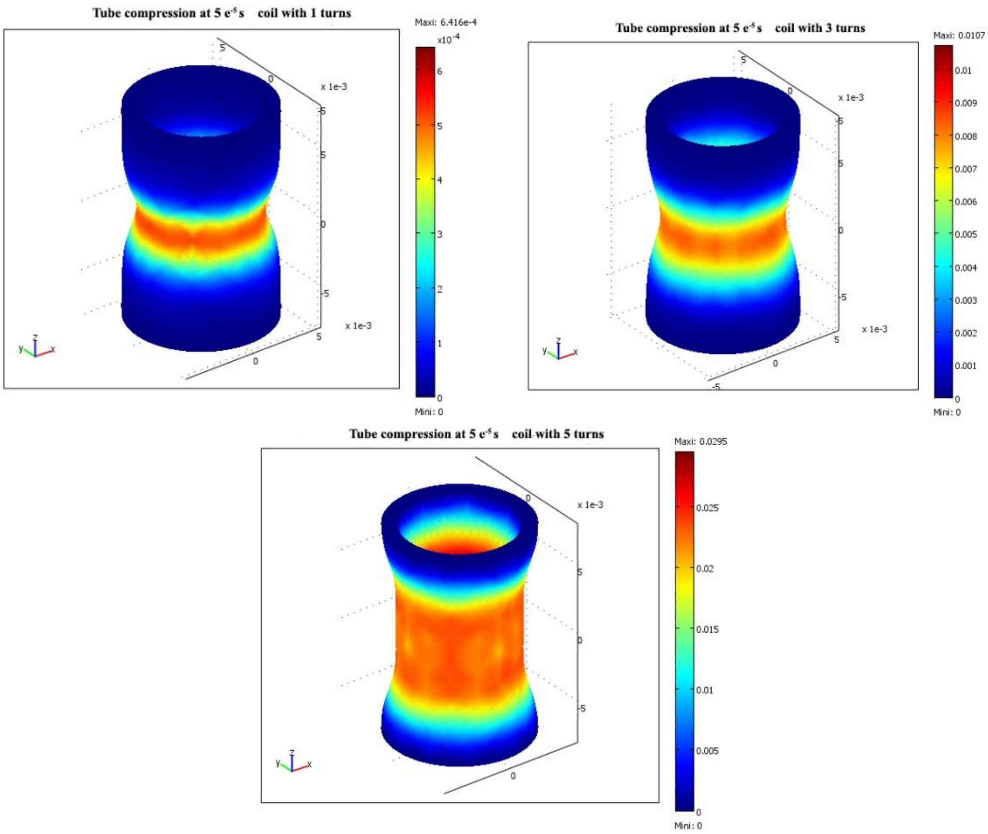

Figure 9. Tubes compressed with different coils

3.3. Flat plate assembly

This application concerns the joining of two parallel flat aluminum plates (50 mm x 50 mm x1 mm) 4 mm apart. The flyer plate is deforming to join with the other fixed plate, under the effect of EM forces generated by the impulse current, which runs through a copper inductor. This coil is 20 mm in diameter and located under the moving plate at a distance of 1 mm (Figure 10). The numerical results of this 3D model, show that the two plates, strike after 28.25 µs. Moreover, the shape of the joining is quite predictable, according to the shape of the considered coil (Figure 11).

On the other hand, we can notice that the assembly of the two plates is more accentuated at t=28.7 µs, and the width of assembly becomes more important (Table 2). Indeed, at t=28.25 µs, the plates present point assembly, the assembled width is less than 3 mm, then this width increases to 7 mm in less than 0.5 µs (Table 2).

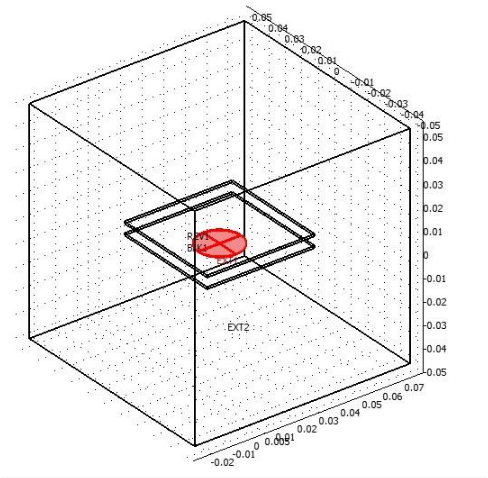

Figure 10. 3D plate assembly system

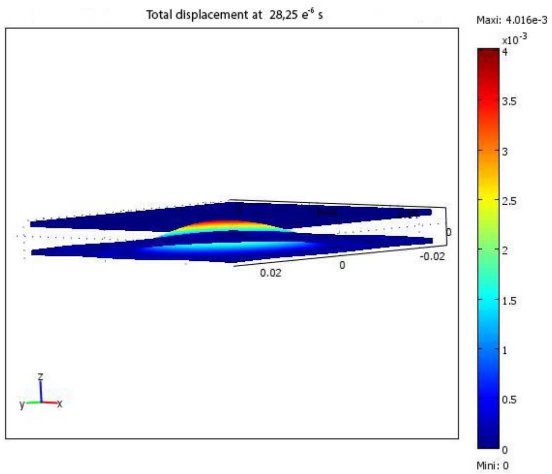

Figure 11. Assembly of plates at t=28.25 µs

Table 2. Characteristics of assemblies at different times

tmax [µs]	28,25	28,4	28,5	28,7
Assembly Width [mm]	2,4	4,6	5,8	7,2
Assembly angle [°]	9,5	8,4	8,13	8

3.4. Tubes assembly

These applications concern installations, which allow the assembly of two Aluminum tubes, either by the expansion of the inner tube or by compression of the outer tube (Figure 12). In the first case, after 18 µs, the two tubes are well assembled at the part facing the coil, where the EM forces are significant (Figure 13). In the case of compression joining, the outer tube deforms to join with the inner one, at the central region surrounded by the compression coil for about 15 µs (Figure 14).

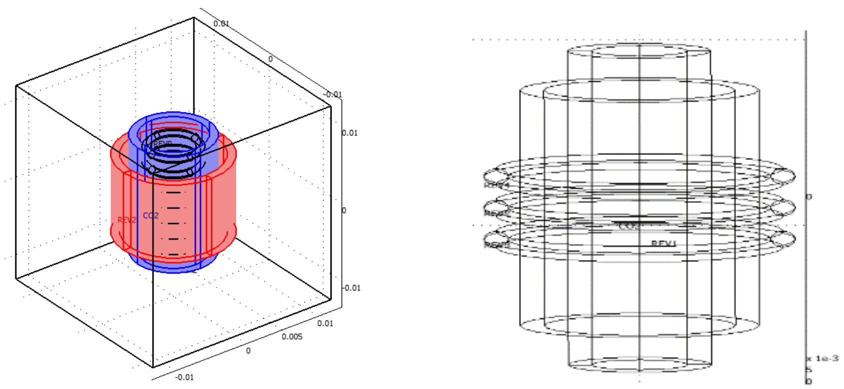

Figure 12. The tube assembly system by expansion-compression

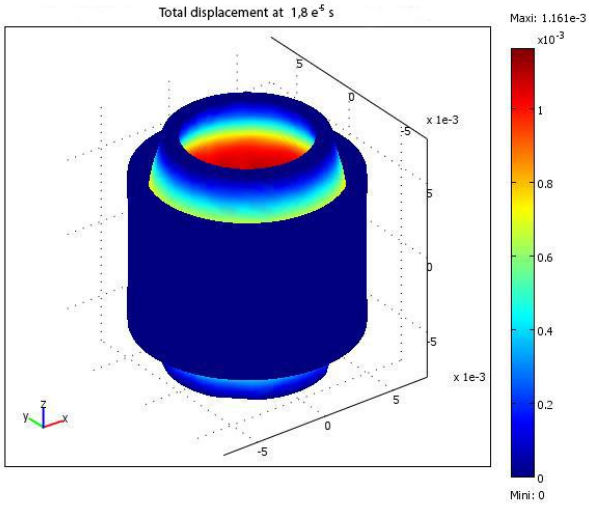

Figure 13. Tubes assembly by expansion

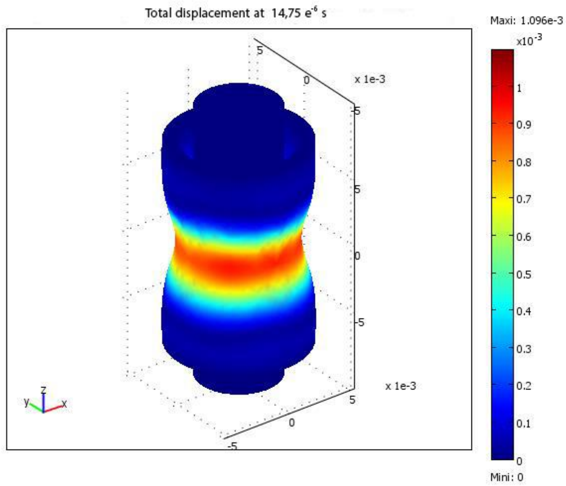

Figure 14. Tubes assembly by compression

4. CONCLUSION

This paper shows an investigation of workpiece deformation that occurs during the EM plate stamping, tube expansion, and tube compression with plates and tubes assembly. These finite element simulations of magnetic forming systems provide important information on both EM and mechanical behaviors. These strong coupling 3D analyses between the two models, EM and mechanical, made it possible to predict the intense EM forces acting on workpieces and consequently, gave the possibility to predict workpiece deformations during the EMF processes and prediction of their final shapes.

Moreover, considering the influence of working conditions, in particular the number of coils turns, the results obtained are theoretically confirmed: The magnetic forces acting are greater in the parts closest to the inductor and different shapes can be obtained by varying the coils forms. The number of coil turns is a crucial parameter. It significantly influences the deformation of the workpiece. This analysis can be extended to more complex shapes and other EMF applications such as welding and hemming processes.

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