FINITE ELEMENT MODEL OF THE MAGNETOFORMING PROCESS

Sorin Pasca [1)] and Virgiliu Fireteanu [2)]

[1)] University of Oradea, Faculty of Electrical Engineering and Information Science
5 Armatei Romane St., 410 087 Oradea, E-mail: spasca@uoradea.ro
[2)] POLITEHNICA University of Bucharest, Electrical Engineering Department
313 Splaiul Independentei, 060 042 Bucharest, E-mail: Virgiliu.Fireteanu@electro.masuri.pub.ro

Abstract*. The paper deals with the numerical modeling of magnetoforming processing for plastic deformation of thin conductive tubes. Transient magnetic finite element analysis by using Flux 2D professional software is performed.*

I. INTRODUCTION

Electromagnetic forming is an unconventional technology of metal working by plastic deformation at room temperature. The principle consists in the deformation of thin metallic pieces by intense impulsive forces acting on the conductor placed in a rapidly varying magnetic field. The device uses a large capacitor bank to store the energy of the process and a spark gap to transfer this energy into the forming coil, as is shown in Figure 1. By discharging the capacitor through the coil, transient magnetic field is produced and eddy currents are induced in the workpiece. Between the coil and workpiece the repulsion forces occur and if the stress in the metallic piece exceeds the yield point of the material, plastic deformation of the piece are produced at a high velocity in a very short time [1],[2],[4].
The forming process involves high frequency, high power, coupled circuits in which the electrical and geometric parameters are time dependent [3].

A rigorous analysis of the system must take into account the non-uniform distribution of the current density within conductors - transient skin effect [1]. In addition, the movement of the workpiece determines induction effects in conductors, modifies the magnetic field distribution, resulting a strong coupling between magnetic and mechanical phenomena.

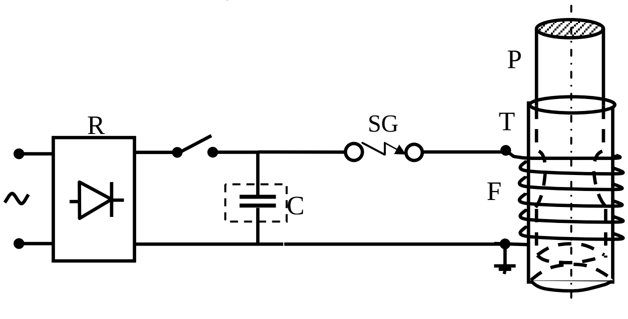

Fig.**1.** The main elements of magnetoforming facility:
R – rectifier, C – capacitor , SG – spark gap,
FC – forming coil, T – workpiece, P – plug

As concequence, the complex interdependence of all system parameters makes the real magnetoforming process very difficult to modeling it. The references gives several approaches developed for study and modeling such systems in condition of some approximations. For example, the reference [1] gives the theoretical model and [3] uses the finite element and macro-element coupling for modeling of magnetoforming device.

This paper presents the possibilities of numerical modeling of magnetoforming systems as a transient magnetic applications using Flux 2D as a software support.

II. MODELS AND FORMULATIONS

The magnetoforming device is an axisymmetrical system in which the transient magnetic field analysis is carried out by solving the magnetoharmonic equation in cylindrical coordinates. The current density in the forming coil that is the source of electromagnetic field has azimuthal orientation $\boldsymbol{J}_{ex} = \boldsymbol{J}_{ex\ \varphi}$ and the time dependent magnetic vector potential $\boldsymbol{A} = \boldsymbol{A}(r, z, t)$ has only azimuthal component. The governing equation in terms of magnetic vector potential is:

$$-\left[\frac{\partial}{\partial r}\left(\frac{\nu}{r}\cdot\frac{\partial}{\partial r}(r\cdot\boldsymbol{A})\right)+\frac{\partial}{\partial z}\left(\nu\cdot\frac{\partial \boldsymbol{A}}{\partial z}\right)\right]+\sigma\frac{D\boldsymbol{A}}{Dt}=\boldsymbol{J}_{ex}\quad, \qquad (1)$$

where $\nu = 1/\mu$ is magnetic reluctivity and $\sigma = 1/\rho$ is electric conductivity of the material, and $\frac{D\boldsymbol{A}}{Dt}=\frac{\partial \boldsymbol{A}}{\partial t}-v\times \mathrm{rot}\,\boldsymbol{A}$, with **v** the velocity. In this paper no motion of workpiece are considered (v = 0) and taking into account the axisymmetric geometry the FEM solution is carried out by using the modified vector potential $r\cdot\boldsymbol{A}$:

$$-\left[\frac{\partial}{\partial r}\left(\frac{\nu}{r}\cdot\frac{\partial}{\partial r}(r\cdot\boldsymbol{A})\right)+\frac{\partial}{\partial z}\left(\frac{\nu}{r}\cdot\frac{\partial}{\partial z}(r\cdot\boldsymbol{A})\right)\right]+\frac{1}{r}\sigma\frac{\partial}{\partial t}(r\cdot\boldsymbol{A})=\boldsymbol{J}_{ex}\quad, \qquad (2)$$

where the second term in the left part of the equation represents the density of induced currents, non-null in conductive regions of the computation domain.

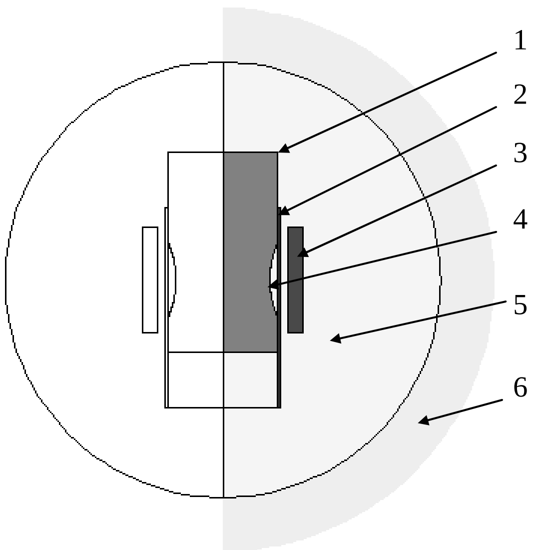

Fig. 2. The computation domain.
1 - shaped bar, 2 - conductive tube
3 - forming coil, 4 - deformation zone
5 – air, 6 – infinite Flux region

The computation domain for a typical magnetoforming application is shown in Fig 2. The source $\boldsymbol{J}_{ex}$, non-null only in coil region, is an unknown value as it follows: if we consider the forming coil as a coil conductor made by thin wire, the current density $\boldsymbol{J}_{ex}$ is constant in whole coil region and if the forming coil is considered as a solid conductor, the quantity $\boldsymbol{J}_{ex}$ is an unknown that reflect the surface distribution of the current.

At any time step, the second relation between $\boldsymbol{A}$ and $\boldsymbol{J}_{ex}$ is given by the model of electrical circuit, so the presented applications consider magnetic field – electric circuit coupling. Fig. 3 presents three variants of circuit model, first one turn coil - stranded conductor, second one turn coil – solid conductor and the last one six turns coil - solid conductor.

Transient magnetic application is solved by step by step in time domain method. The value of the time step must be evaluated, in accordance with the period T of damped oscillation of circuit. A time step equal to $(1/40)\cdot T$ determines a good accuracy of results [5].

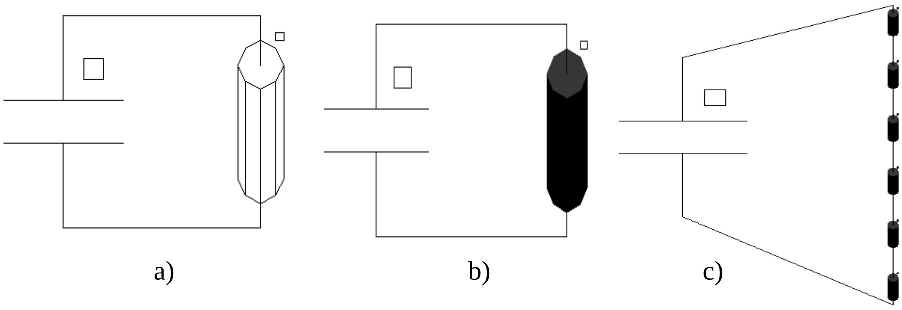

Fig. **3**. Circuit models: stranded conductor coil (a) and 1 turn (b) or 6 turns coil (c), solid conductors

By the other side, the meshing of the calculus domain must take into account the effect of magnetic field diffusion. For this purpose, it is necessary to estimate the penetration depth δ in the solid conductors for a good adaptation of the mesh.

III. APPLICATIONS AND RESULTS

The application consists in the study of electromagnetic transient regime associated with the magnetoforming process of 1mm thin aluminum tube over an aluminum shaped bar in

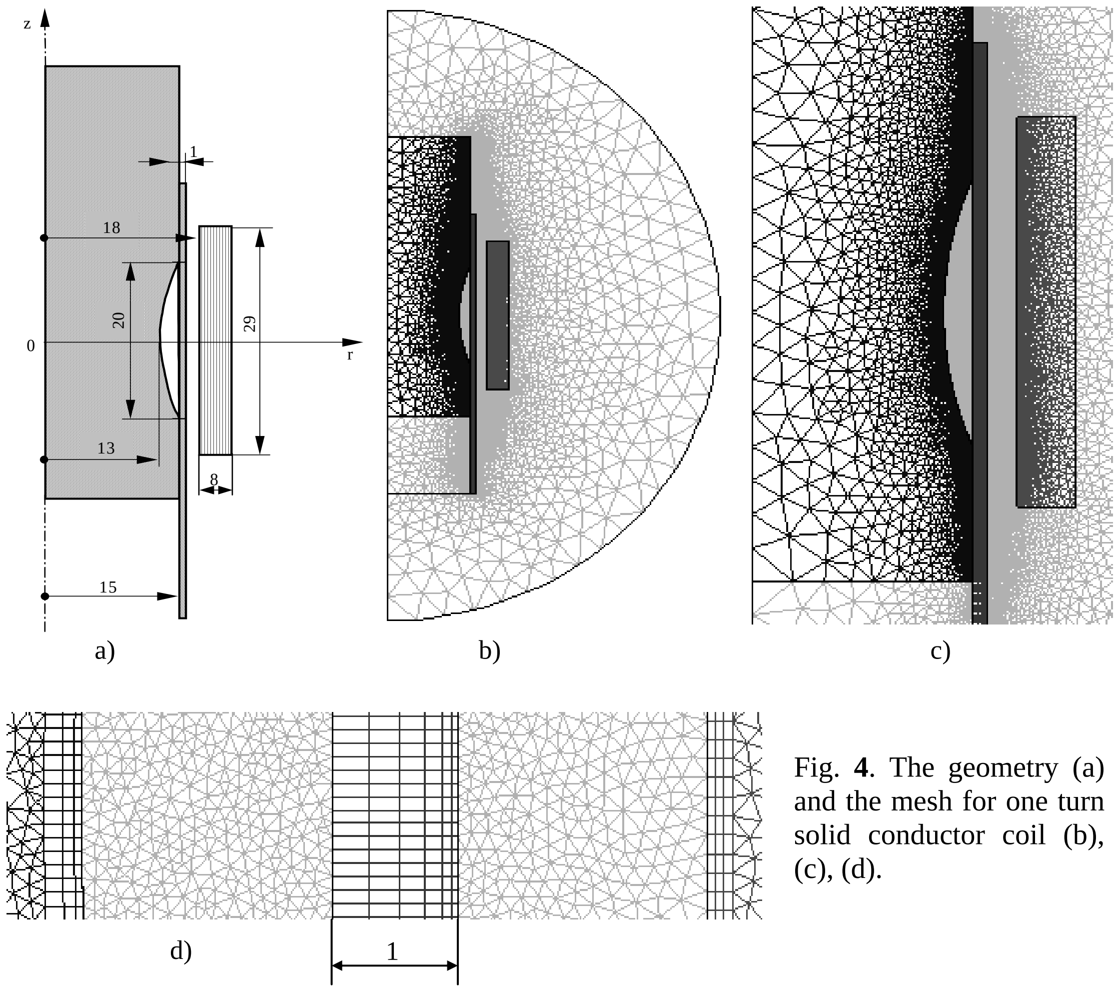

Fig. **4**. The geometry (a) and the mesh for one turn solid conductor coil (b), (c), (d).

order to couple them. The computation domain is the same as in Fig. 2 and geometry dimensions are given in axial section in Fig. 4a. We study the application on 3 variants, corresponding at circuits shown in Fig. 3. The mesh characteristics for solid conductor coil are shown in Fig. 4b, c, d.

The materials properties are as follows: the rezistivity $3.4\cdot10^{-8}$ Ωm for aluminum and $1.75\cdot10^{-8}$ Ωm for electrolytic copper of solid coil conductor. The yielding point of tube is 25 N/mm^2. The magnetic permeability of vacuum $\mu_0 = 4\pi\cdot10^{-7}$ H/m is considered for all computation domain. A Dirichlet boundary condition is considered for all external boundary of te computation domain. The initial (t = 0) voltage of the capacitor of 500 μF is $U_0 = 1000$ V.

Fig. 5 shows the equiflux lines in the computation domain, for the first circuit case and Fig. 6 the flux density chart at the moment when the coil current reaches the maximum value. The time dependence of the coil current is represented in Fig. 7. For this case, we found the period T = 12.9 μs , respectively the frequency f = 77.52 kHz, and the time corresponding to the maximum of the current, t_{max} = 3 μs. At this moment, I_{max} = 219.43 kA, B_{max} = 12.09 T. The values of time are in accordance with the time step, sets at 0.1 μs.

The time variation of the stress on the tube workpiece during the transient process is shown in Figure 8. The maximum radial strain is 193.98 N/deg and is obtained at the time t_{max} On the outer surface of the tube this value gives an effort of about 463 N/mm^2 greater than the yielding limit 25 N/mm^2, and the deformation is produced easy.

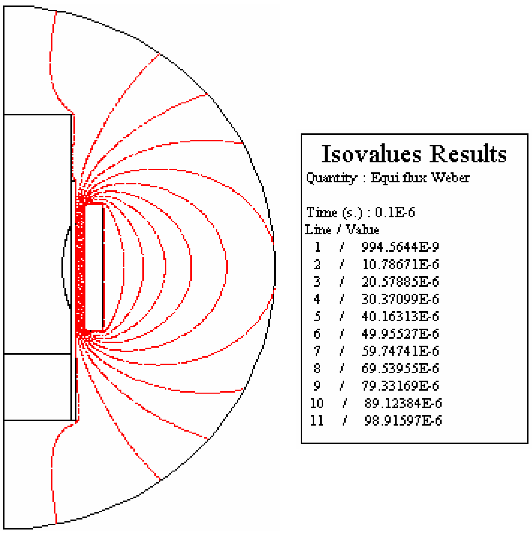

Fig. **5**

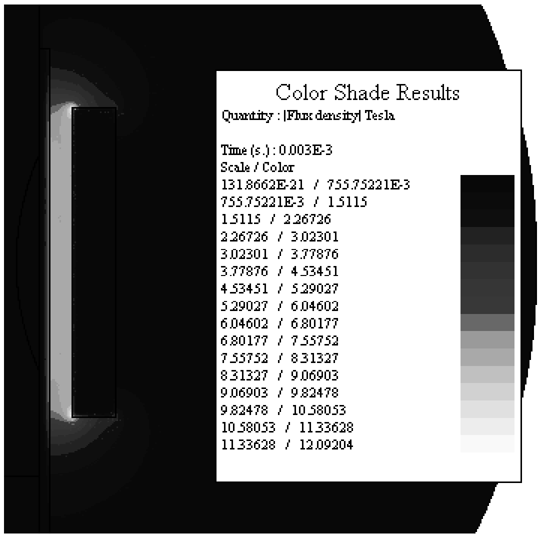

Fig. **6**

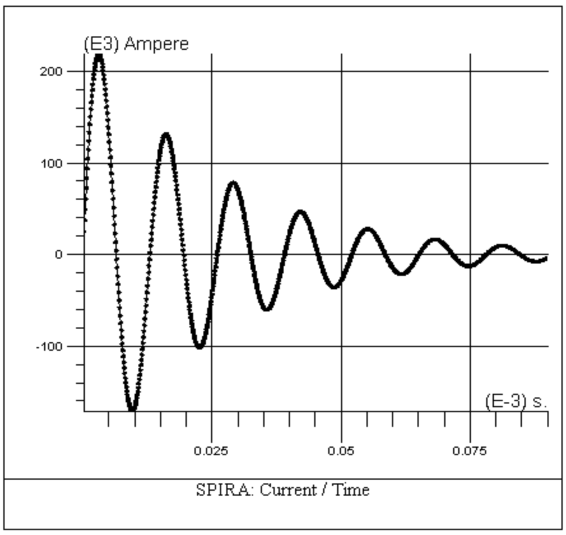

Fig. **7**

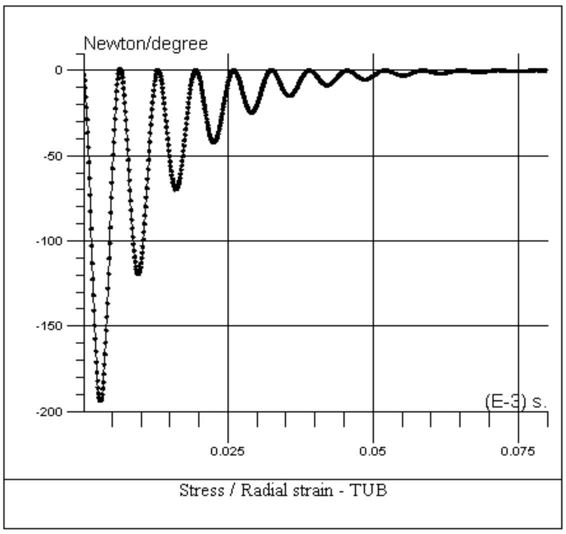

Fig. **8**

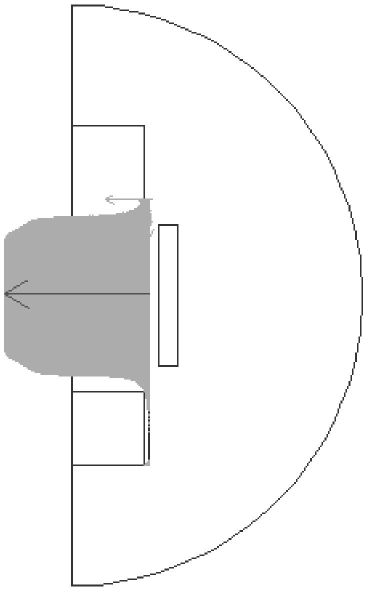

Fig. **9**

The charts of different quantities of electromagnetic field on different regions of the computation domain, e.g. current density, volume density of electromagnetic force can be obtained. Fig. 9 shows the vectors of volume density of electromagnetic forces acting on tube region.

In the second case, when 6 turns of solid conductor type represent the forming coil, the mesh has the same properties on the skin depth of conductors like in previously case. A detail presented in Fig. 10 shows the quality of mapped mesh in these zones. We found a period T = 88 μs, f = 11.36 kHz; the time step is 2 μs and number of steps 300. The time variation of the current shown in Fig. 11 gives the maximum of 28705 A at t_{max} = 18 μs. The maximum radial stress is 112.91 N/deg and the corresponding effort 269.57 N/mm^2 is also greater than the yielding limit. Fig. 12 presents the time variation of the radial stress on tube.

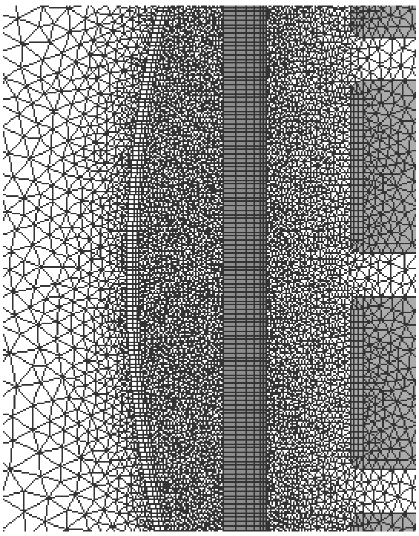

Fig. **10**

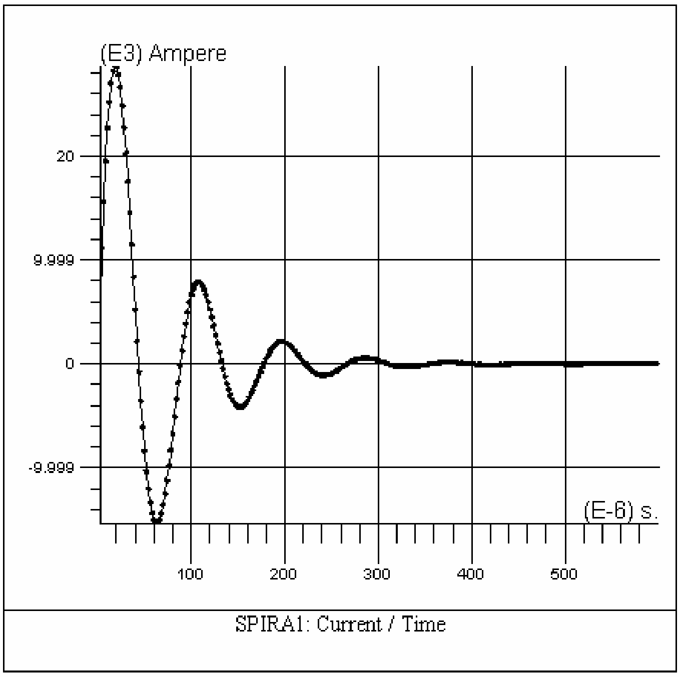

Fig. **11**

Finally, in the last case, when we consider the forming coil of stranded conductor type, with uniform distribution of the current source in the cross-section, the mesh has a smaller number of elements. The results are: T = 100 μs, f = 10 kHz, t_{max} = 22.5 μs, I_{max} = 157088 A. The maximum radial stress on the tube is f_{max} = 88.61 n/deg and the specific effort is σ_c = 211.54 N/mm^2 >> 25 N/mm^2. The time variation of the force that compresses radially the tube is presented in Fig. 13.

From the circuit model, we can know the time variation of electrical parameters, as shown in Figure 14.

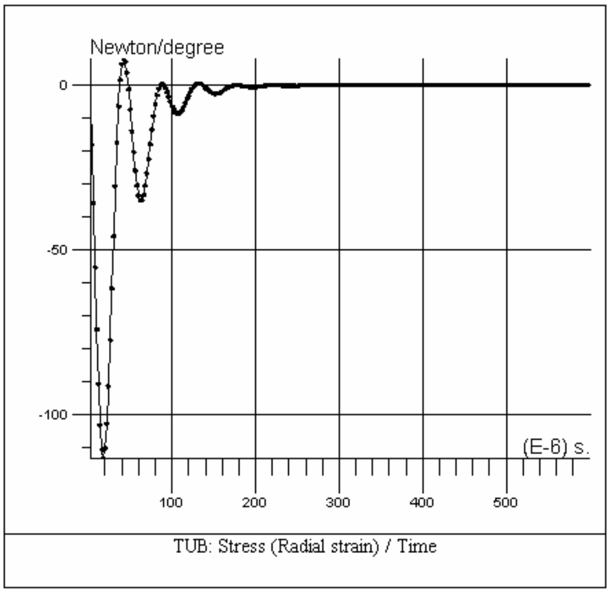

Fig. **12**

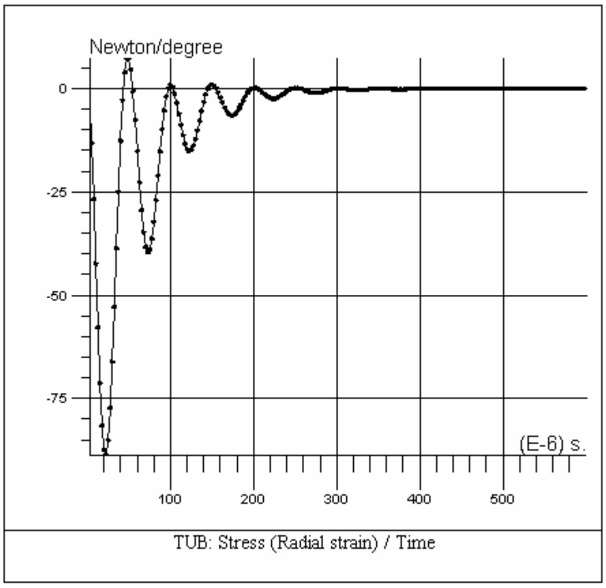

Fig. **13**

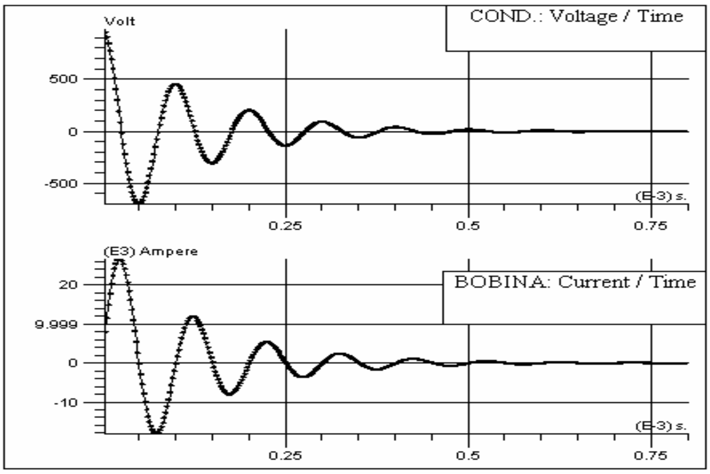

Fig. **14**. Time variation of voltage and current in electrical circuit

IV. CONCLUSION

The results presented in the paper are in a good agreement with the data from different references. Since the movement of workpiece is neglected in our model, the computations are useful to predict if the impulsive forces are as great as is necessary for plastic deformations.

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