NUMERICAL INVESTIGATIONS ON PARTICULAR APPLICATION OF ELECTROMAGNETIC FORMING

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ABSTRACT: The paper deals with numerical investigations on some special application derived from electromagnetic forming, such as pulse magnetic compaction of powder materials. Based on finite element models, it is computed the characteristic parameters and quantities of the process, in order to identifying the possibilities to improve the efficiency. It is evaluated the influence of the thickness of thin copper driver and of the stored energy in the capacitor bank.
KEYWORDS: electromagnetic forming, electromagnetic compaction, numerical modeling, pulsed magnetic compaction

1. INTRODUCTION

In the last few years, due to multiple advantages, the use of workpieces made by aluminum and its alloys has extended in many sectors e.g. in automotive industry. As a consequence, taking into account the particularities in processing such materials, some classical technologies are improved but, because these processes often are not satisfactory, new unconventional technologies are initiated and developed.

High rate forming technologies such as electromagnetic forming, hydro-forming etc., used only in some special application in ’60-’70 and rarely used later, especially due to an insufficient control at that time, becomes in last decades actually.

Electromagnetic forming or magnetoforming is a high speed forming process where a pulsed magnetic field is used to processing metals with high electrical conductivity (aluminum, copper or their alloys) within a few microseconds. Usually, thin wall metallic pieces (sheets, tubes) are deformed at room temperature by intense impulsive forces generated by a rapidly time varying magnetic field.

But, as the ultra-fast electromagnetic deformation process was better controlled, the range of this type of applications has extended a lot. In the past few years, many scientific papers [1,2,3,4,5,6] analyses new processes such as electromagnetic impact welding or pulse-magnetic compaction of metal powder or of ceramic powder.

After in previous work, we analyse different strategies in numerical modeling of magnetoforming process of thin wall metal sheets and tubes [7,8,9,10], in this paper we investigate the pulse-magnetic compaction of powder materials. The finite element model are build, having as a support the professional software Flux™. The process is treated only as transient magnetic application. The intimate processes that take place in the powdered material when it is compressed are not taken into account. The main goal is to estimate the electromagnetic forces that act to compact the powder material.

2. MAGNETIC PULSED COMPACTION FACILITY

Figure 2 presents the main elements of magnetic pulsed compaction equipment. The powder material (9) is placed into a rigid mold (8) and it will be pressed by a punch (7) provided with a flat cap (6). The flat coil (3) is supplied by adjacent electrical circuit, consisting in a capacitor bank capable to store enough amount of energy and a spark-gap as switching equipment. The charging of capacitors is ensured by a rectifier (13).

Because the principle of pulse magnetic technologies requires a high conductivity material, a “driver” made by copper is placed as a layer on upper surface of cap punch (low conductivity steel). In fact, the driver is the active element, because in it are located the repulsive forces which are produced as a result of interaction between currents through coil turns and induced currents in copper driver. As the coil current can reach tens to hundreds kA, depending of stored energy and values of circuit parameters, the Lorentz forces can achieve very high values for a very short time (impulse). Between flat coil and driver is a thin layer of insulator, both electrical and thermal, e.g. mica based. The insulation between coil turns (2) can be made from an epoxy resin. The whole assembly is strengthened by two rigid frames, upper (1) and lower (10).

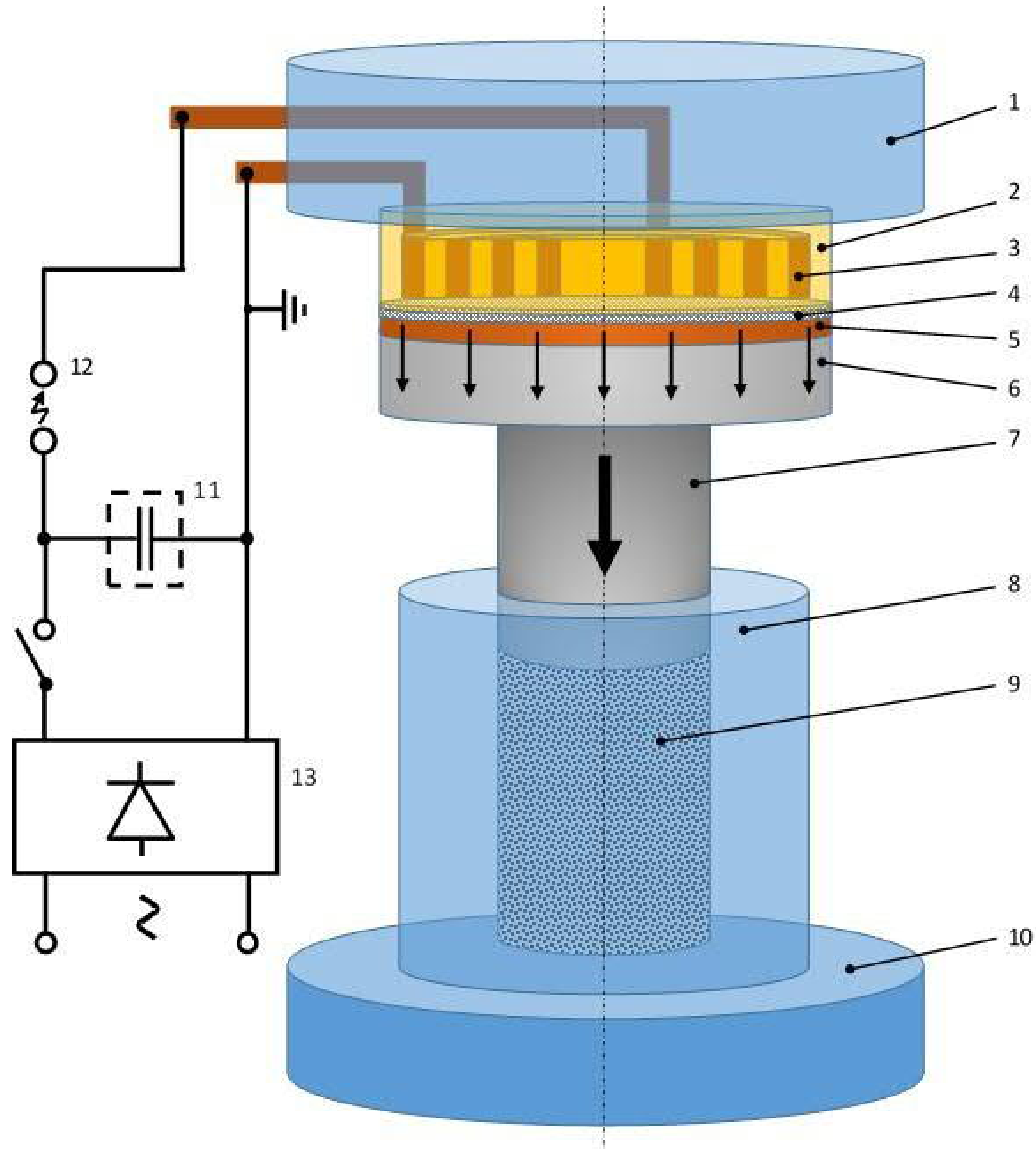

Figure 1. Main components of facility used for pulsed magnetic compaction of powder materials. 1 – upper frame, 2 – electrical insulation between coil turns, 3 – coil turns, 4 - electrical insulation between coil and driver, 5 – driver sheet made by high conductivity metal, 6 – cap, 7 – punch, 8 – mold, 9, compacted powder material, 10 – lower frame,11 – capacitor bank, 12 – spark gap, 13 – rectifier

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3. THEORETICAL BACKGROUND

The pulsed magnetic compaction device presented above can be considered, with a sufficiently good approximation, as having axial symmetry. Consequently, this system with axisymmetric geometry can be studied in 2D, in *rOz* coordonate system. As we stated in the introduction, only transient magnetic problem are analysed, neglecting in this case the effects generated by temperature rise in coil and driver, as well as the complex mechanical phenomena related to powder compaction. In previous works we studied the coupling electromagnetic – thermal – mechanical phenomena, by treating electromagnetic forming processes as a multiphysics applications [7,8,9,10].

The current density in the coil, that is the source of electromagnetic field, has azimuthally orientation, $\boldsymbol{J_{ex}} = \boldsymbol{J_{ex\,\varphi}}$. As a consequence, the time dependent magnetic vector potential $\boldsymbol{A}(r, z, t)$ has component only in the same direction. The governing equation in terms of $\boldsymbol{A}$ is:

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

where ν is magnetic reluctivity and $\sigma = 1/\rho$ is electric conductivity. The total derivative in (1) has the expression $\frac{D\mathbf{A}}{Dt}=\frac{\partial\mathbf{A}}{\partial t}-v\times\mathrm{rot}\,\mathbf{A}$, with v the velocity. If the motion is not considered (v=0) the equation of the vector potential in $r\cdot\boldsymbol{A}$ is:

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

The second term in the left part of the equation represents the density of induced currents, non-null in the conductive regions of the study domain. This equation of state variable $\boldsymbol{A}$ of transient magnetic field is solved using the step by step in time domain method. The 2D electromagnetic computation domain for the magnetic compacting application, in which the device has axial symmetry, is shown in Figure 2.

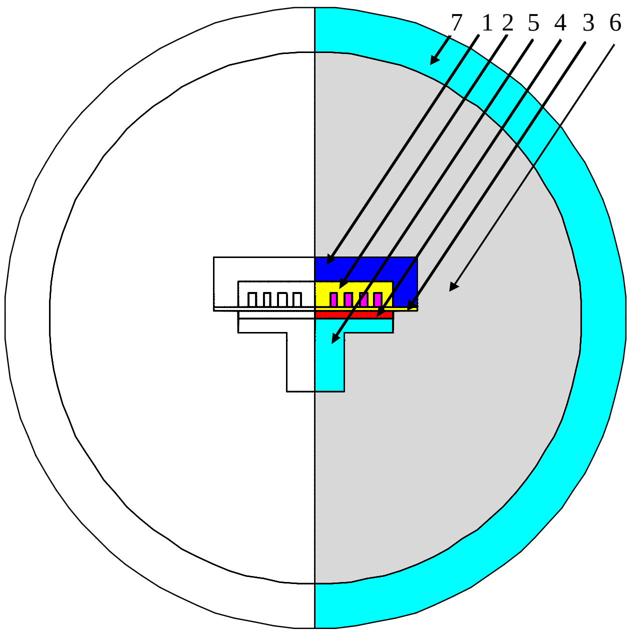

Figure 2. Magnetic pulse compaction – 2D computation domain: 1 – magnetic shield, 2 – electrical insulation, 3 – insulation coil – driver, 4 – copper driver, 5 – punch, 6 – surrounding air, 7 – infinite region

The source $\boldsymbol{J}_{ex}$, which is non-null only in coil region, is an unknown value as it follows: if the flat coil is of thin wire type, the current density $\boldsymbol{J}_{ex}$ is constant in whole the coil region and if the forming coil is of solid conductor type, the current density is not constant over the coil cross-section.

At any time step, the second relation between $\boldsymbol{A}$ and $\boldsymbol{J}_{ex}$ is given by the model of electrical circuit, so the magnetic field – electric circuit coupling is considered. In some studies, a measured current is used as excitation for the simulation of the process in coupled simulations [11], but the necessity of preceding measurements is unsatisfactory when simulation tools are applied to predict the process result.

The equation of magnetic vector potential being solved iteratively in time domain, the value of the time step must be evaluated in accordance with the period T of damped oscillation of circuit. For example, a time step equal to (1/40)·T·determines a good accuracy of results.

The electromagnetic interaction involves repulsive forces between the coil and copper driver. By computing the force vector in each element of the driver, at each time step, it is possible to estimate the compressive action of the punch to the powder material in the mold.

By the viewpoint of current source in the calculus domain, there are two possibilities. One consists of giving the excitation current density in the coil region as a time dependent total current or a time dependent current density. Frequently, these dependencies are obtained from experimental measurements on device that is the subject of analysis.

Another method, more realistic and preferred in this work, is to take into account in the analysis of the electrical circuit – magnetic field coupling. In this case, the source current density in the coil results by solving electrical circuit equations:

$$(L_1+L_c)\frac{di_1}{dt}+\frac{d}{dt}(Mi_2)+(R_1+R_c)i_1+\frac{1}{C_e}\int i_1 dt=0 \quad (3)$$

$$\frac{d}{dt}(L_2 i_2)+\frac{d}{dt}(Mi_1)+R_2 i_2=0 \quad (4)$$

where i_1 is the coil current, i_2 is the total current in driver (the sum of eddy currents induced in driver copper), L_1 and R_1 are the resistance and inductance of the coil, L_2 and R_2 – the same parameters for driver, R_c, L_c are the resistance and inductance of connecting conductors (neglected in this analysis), M is the mutual inductance between coil and driver and C_e is the equivalent capacity of capacitor bank.

The initial conditions for (3) and (4) are:

$$i_1=0; \quad (L_1+L_c)\frac{di_1}{dt}=U_0; \quad i_2=0 \quad (5)$$

where U_0 is the initial value of the capacitor voltage.

Taking into account the coupling between circuit and finite element domain, it is obviously that the magnetic compaction circuit and device is treated as a distributed parameters system. As a consequence, the values of parameters that appear in (3) and (4) result from numerical calculus.

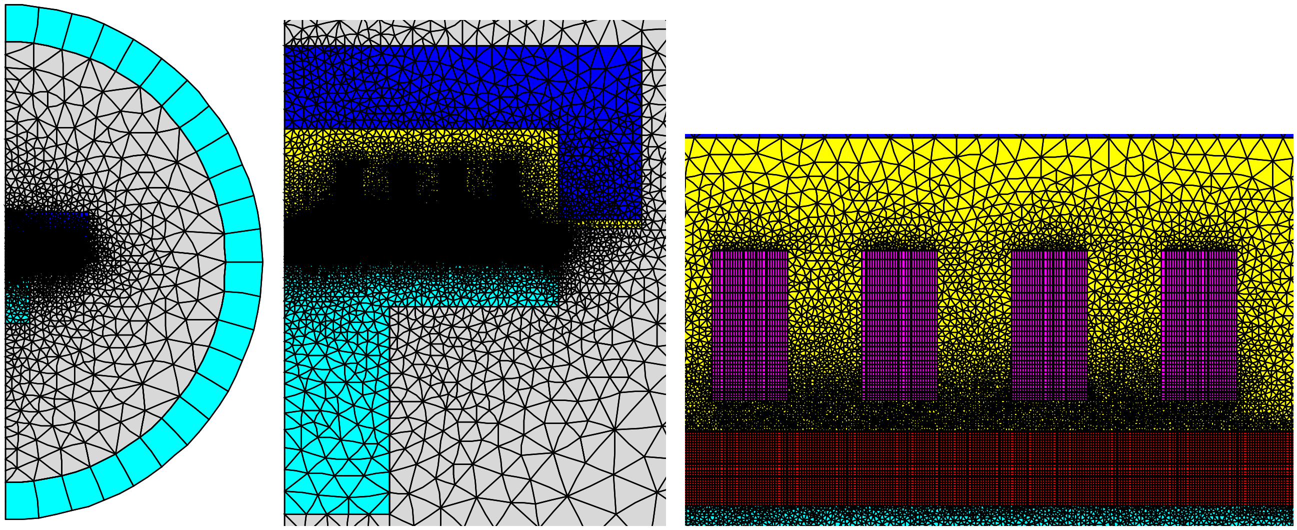

Figure 3. Details of the mesh of computation domain

Figure 3 shows the mesh details that must be adapted to current density distribution. In the massive conductor regions, for accurate results it is important to have at least two finite elements along to skin depth of electromagnetic field. This must be verified in accordance with frequency reached in discharging process.

4. THE APPLICATION AND RESULTS

The application consists of a parametrical study of electromagnetic transient regime associated with the pulsed magnetic compaction process. The parameters of the model that can by modified in the study are presented in Table 1 ..

Table 1. The parameters of the model

No.	Parameter name	Parameter signification	Initial value
1.	ASPIRA	radial dimension of cross-section of turn coil	5 mm
2.	BSPIRA	radial dimension of cross-section of turn coil	10 mm
3.	HDRIVER	thickness of copper driver	5 mm
4.	HMICA	thickness of insulation between flat coil and driver	2 mm
5.	INTRESP	thickness of insulation between coil turns in radial direction	5 mm
6.	GROSECRAN	thickness of magnetic shield (optional)	16 mm
7.	DINTIND	inner diameter of the coil	20 mm
8.	DDOP	diameter of punch	40 mm
9.	HDOP	the axial dimension of punch	40 mm
10.	HCAPDOP	the axial dimension of punch cap	10 mm
11.	C	equivalent capacitance of capacitor bank	200 μF
12.	V0	initial voltage of capacitor bank	1000 V

For the initial values of model parameters given in Table 1, Figure 4 presents the time variation of capacitor voltage and of the coil current, as well as the lines of magnetic flux and the chart of flax density at the time of 9 μs, when the current riches the maximum value of 27.52 kA. It is observed that on the upper surface of the driver, for a very short time, it is obtained values of flux density greater than 4 T. At this moment of maximum current through the coil, the chart of current density in driver and the distribution of volume density of electromagnetic force is illustrated in Figure 5.

The computation of the axial component of the total force acting on driver at the moment of maximum current through the coil give the value of 20.64 kN. Figure 6 presents the time variation of the axial component of electromagnetic force acting on copper driver during the capacitor discharge process, assuming that no motion is produced, i.e. the punch remains in the initial position. Finally, Figure 7 shows the same variation of axial components of force, obtained for the capacitor bank with the same capacitance but charged initially at voltage of 5 kV. In this case, the resulting forces are much bigger, as it is expected.

It is obvious that the parameters that give the energy of the process will be chosen in accordance with characteristics of powder material.

Another observation it's about mechanical stress acting on punch cap. Based on simulation, we can choose the geometry and the thickness to avoiding its destruction.

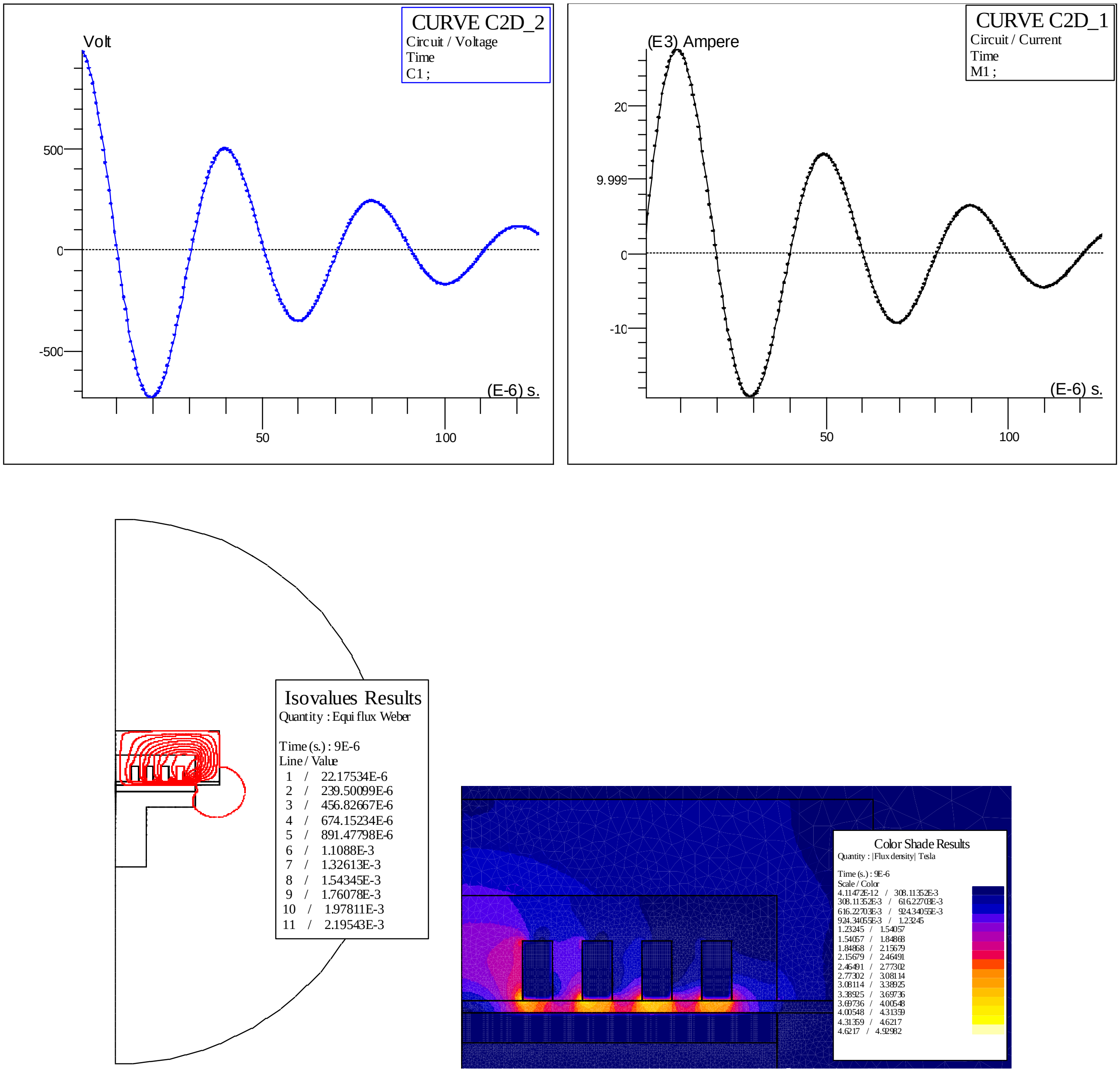

Figure 4. Time variation of capacitor voltage (a) and coil current (b). Equiflux lines (c) and chart of flux density (d) at the moment when coil current reaches its maximum value

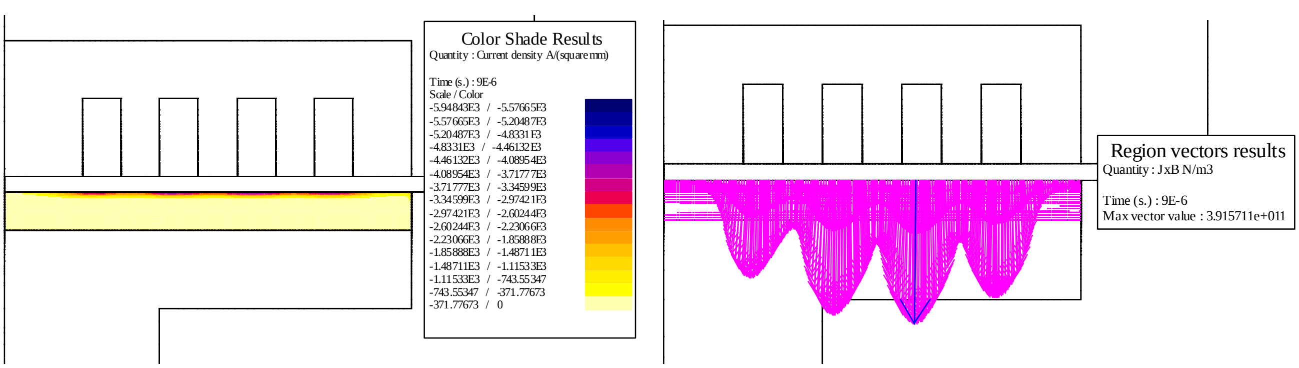

Figure 5. The chart of current density in copper driver (a) and the vectorial representation of volume density of electromagnetic force acting on the driver at the moment of maximum current through the coil

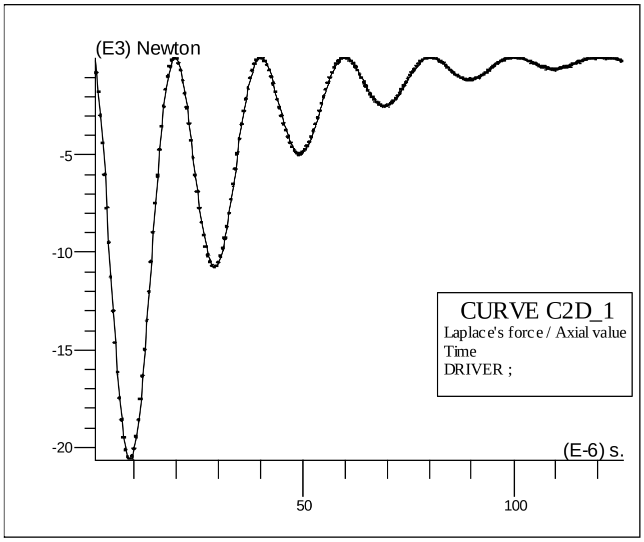

Figure 6. Time variation of the axial component of electromagnetic force acting on copper driver during the compaction process (no motion of punch is considered)

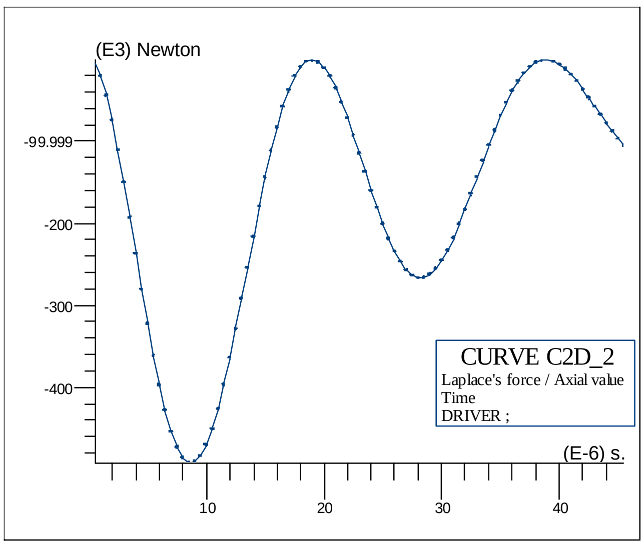

Figure 7. Time variation of the axial component of electromagnetic force acting on driver during the compaction process, for capacitor bank charged initially at 5 kV

5. CONCLUSIONS

The paper presents partial results on numerical modeling of pulse magnetic compaction. Based on finite element model, the transient magnetic field in magnetic compaction device is analysed. No motion or mechanical effects derived from powder compaction are considered.

This type of numerical investigations is useful in order to estimate the optimal values of system parameters for a desired total force acting on punch, which ensures a good powder compaction. It should be mentioned that the experimental validation of the numerical model is absolutely necessary.

Future work will be focused on two directions: first, the heating of coil turns and driver must be evaluated as well as the effects of temperature rise on materials properties and, the displacement of punch under the action of electromagnetic forces, taking into account the mechanical strength of the powder at the motion of the punch can be computed.

6. REFERENCES

1. S.D. Kore, P.P. Date, S.V. Kulkarni, Electromagnetic impact welding of aluminum to stainless steel sheets, *J. of Materials Processing Technology*, Vol. 208, pp. 486 - 493, (2008).
2. V Mironovs, A Korjakins, A Tatarinov, E Barone and V Glushchenkov, Combined static-dynamic compaction of metal powder and ceramic materials, *IOP Conference Series: Mat. Sci. and Engg*, Vol. 251, pp. 1-7, (2017).
3. V. Mironov, A. Tatarinov, M. Kolbe, V. Gluschenkov, Detachment of Conductive Coatings by Pulsed Electromagnetic Field, *7th International Conference on High Speed Forming*, Dortmund, Proc., pp. 69-77, (2016).
4. Chelluri, B., Knoth, E., Powder Forming Using Dynamic Magnetic Compaction, *Int. Conf. on High Speed Forming*, Proc., pp. 26-34, (2010)
5. Shiwei Yan, Shangyu Huang, Wei Liu, Jianhua Hu, Yu Lei, Mengcheng Zhou, Exp. and num. investigation of temperature evolution during electromagnetic pulsed compaction of powders, *Powder Technology*, Vol. 306, pp. 1-9, (2017).
6. S.J. Hong, G.H. Lee, C.K. Rhee, W.W. Kim, K.S. Lee, Magnetic pulsed compaction of ferromagnetic nano-powders for soft-magnetic core, *Materials Science and Engineering*, Vol. 449–451, March 2007, pp. 401-406, (2007).
7. S. Pasca, T. Vesselenyi, V. Fireteanu, T. Tudorache, M. Tomse, P. Mudura, E. Vladu, S. Muresan, Sequentially Coupled FE Model of Transient Magneto-Structural Phenomena in Electromagnetic Forming Processes, Int. Symp. ATEE, Bucharest, pp. 197-202, (2008).
8. S. Pasca, T. Tudorache, M. Tomse, Finite Element Analysis of Coupled Magneto-Structural and Magneto-Thermal Phenomena in Magnetoforming Processes, *Int. Conf. Electromagn. Processing of Materials*, EPM Dresda, Proc. pp. 735-738 (2009).
9. S. Pasca, V. Fireteanu, Finite Element Analysis of Successive Induction Heating and Magnetoforming of Thin Magnetic Steel Sheets, *14th Int. Symp. on Num. Field Calc. in Electrical Engg. IGTE*, Graz, Austria, Proc. CD, (2010).
10. S. Pasca, A. Pasca, Numerical Modeling of High-Speed Free Bulging of Thin-Wall Aluminum Tubes under the Action of Impulse Electromagnetic Forces, JEEE, Vol. 8, No. 1, pp. 27-30, (2015)