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Simulation of magnetic transitory parameters at electromagnetic forming of metal sheet

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Abstract. Proposed and accomplished finite element simulations in this paper started from the idea that materials which are plastically deformed and those from which electromagnetic deformation devices are built can influence the development of transitory magnetic phenomenon during the working process. Workpieces from paramagnetic, diamagnetic and ferromagnetic materials and devices that contain metallic and non-metallic materials were taken into study. FLUX2D modelling and simulating software was used to achieve numerical values and graphical images for the main process parameters: magnetic induction and magnetic pressure (of deformation). A finite element model, previously validated through experiment, was used to perform the simulations in order to assure a high degree of accuracy for the presented results.

Keywords: Simulation; Finite element; Transitory parameters; Electromagnetic forming.

1. Introduction

Electromagnetic forming procedure is part of the metals processing procedures with great energies and high-speeds. A concentrated energy source is used for these procedures, energy which is released in a very short time on the workpiece. As energy sources for the electromagnetic forming procedure, pulsed magnetic fields are used.

The development of electromagnetic forming technology is nowadays demanded by automakers, who want to introduce aluminium sheet in the manufacture of the deep-drawn parts for body components [1-4]. Also, vehicle's motor weight reduction is reached by introducing lightweight materials in the automotive and aeronautics industries [5, 6]. Electromagnetic forming of tubular components is an innovative joining process for lightweight materials.

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The request for the development of metal sheets electromagnetic forming is related to: (*i*) the elaboration of design criterions for forming devices (flat spiral coils, dies); (*ii*) durability problems of flat spiral coil; (*iii*) establishing the formability of the workpiece material; (*iv*) numerical modelling of the process (magnetic field, stresses, strains, temperatures), regarding transitory phenomenon that occur; (*v*) the influence of forming die [7] and workpiece materials, as well as the interactions that occur in the presence of high intensity magnetic field.
Advantages of using electromagnetic forming technology: (*i*) great technological flexibility, several different forming operation can be implemented with the same equipment by changing the working device; (*ii*) the productivity is high because the electromagnetic character of the procedure is not limited by mechanical inertia of some moving elements (tools, press ram etc.); (*ii*) the forming pressure is not the result of a mechanical contact between a tool and the workpiece, thus the initial surface quality of the workpiece is not affected; (*iv*) allows the joining of workpieces to be made of same [8] or different materials; (*v*) the increase of the workpiece material formability [9, 10]; (*vi*) as a results of minimal springback close tolerances are possible; (*vii*) the process is clean, lubricants not being necessary.
In this paper, simulations of transient magnetic parameters (induction and pressure) were made at the electromagnetic deformation of ferrous and non-ferrous metallic materials, with devices which have in their build metallic and non-metallic materials.

2. Magnetic induction, pressure and velocity of deformation

The principle of electromagnetic forming procedure is known and it is based on electromagnetic induction principle, being clearly exposed in paper [11]. Therefore, electromagnetic forming is based on the repulsion phenomenon of magnetic fields, generated by the inducting current that passes through the coil (tool) and the inducted current that passes through the workpiece. The pressure developed in the process must be great enough (greater than the flow limit of the workpiece material) so it can give the material the kinetic energy necessary for plastic deformation, in the short time that the magnetic pulse occurs. The pressure p obtained is directly proportional to magnetic induction (B) and the magnetic field's intensity (H), according to the following relationships:

$$p = B^2 / 2\mu_0 \quad (1)$$

$$p = 0.91 \cdot H^2 \quad (2)$$

where, μ_0 is the magnetic permeability of the space between coil and workpiece.
This deformation pressure, of special character (magnetic nature), has two big advantages: (*i*) its size can be controlled/adjusted very precisely, thus using only the energy necessary to deform, without consuming while idle; (*ii*) deformation pressure is not the result of a physical contact between the tool and workpiece and as a result the part is achieved with the same surface quality as the one of the

workpiece material.
From a technological point of view, the high-speed of the occurring physical processes is specific; this makes the plastic deformation produced to have a viscoplastic character. Deformation velocity v is an important element for defining the mechanism of electromagnetic forming and it is determined with the following relationship:

$$v = p \cdot t / m \quad (3)$$

where, p is instantaneous deformation pressure, t is pulse's duration and m is mass related to surface unit.
Researches of the velocity achieved by the workpiece at impact with the deep-drawn die showed values of 150 m/s for usual steel and aluminium sheets and 140 m/s for copper sheets. The high-speed from electromagnetic forming has very important consequences, strongly influencing both the processes progress and the final results, like: (*i*) it can modify the ductile-fragile transition; (*ii*) together with the temperature it adjusts the forming mechanisms; (*iii*) it influences the resistance at plastic deformation; (*iv*) it has consequences on the structure, influencing the thermodynamic conditions, the recrystallization kinetics and the phase transformations with or without diffusion. All this explain the known phenomenon of formability increase of some materials, later called „hyperplasticity" and mentioned in numerous papers [12-14].
The dependency that exists between pressure, velocity and displacement in the case of electromagnetic forming was established as a result of some researches (Figure 1).

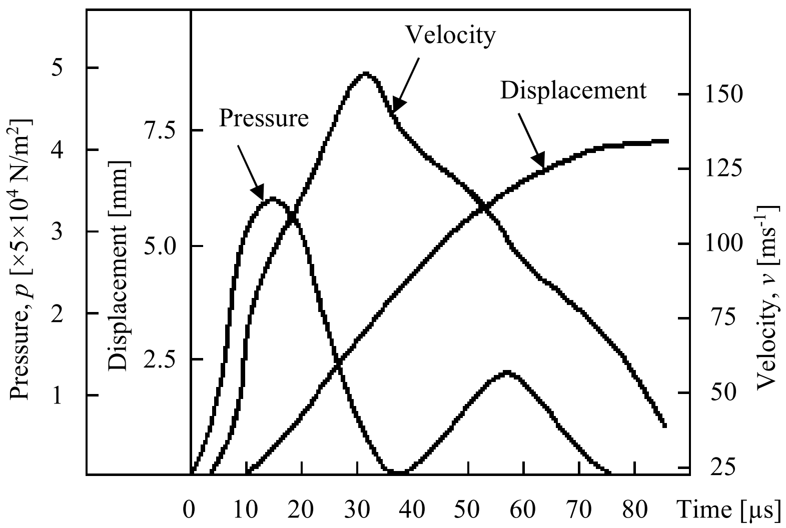

Fig. 1. Pressure, velocity and displacement variation depending on time.

From the Figure 1 we can observe that the deformation pressure exceeds the static flow limit of the material, before it suffers deformations (however small). The

magnetic energy from the existing space between the coil and the workpiece grows and, after the forming begins, the magnetic energy transforms into kinetic energy that acts on the material, under the form of deforming mechanical work.
The maximum deformation velocity is achieved after the highest value of the pressure has been achieved, along the pulse's duration current losses diminish the magnetic energy, through heat loss into the tool coil, as well as into the processed part.

3. Simulation results and discussions

A finite element model, previously validated through experiment [15], was used to perform the simulations, in order to assure a high degree of accuracy for the presented results. From the viscoplastic process' point of view, which occurs at electromagnetic forming, the working parameters that interest the most are [16, 17]: magnetic induction, produced by the coil, and the deformation pressure, that is created in the space between the coil and the workpiece. The simulations performed within these studies aimed to emphasize the action way of magnetic induction during manufacturing by means of electromagnetic forming of different nature metallic materials. The materials chosen for the specimens were Cu-OF cooper, EN AW-3105 aluminium alloy and FeP04 steel, for which specific material properties were indicated. The thickness of disk specimens was of 0.5 mm. The used simulation parameters, as well as results obtained in the above three cases are shown in Figures 2 and 3.
The studies concerning deformation pressure were accomplished in two different cases (Figure 4): (*i*) for a *real device* that was used for research and contains steel elements (case 1); (*ii*) for a *virtual device* for which steel elements were replaced with polyamide elements (case 2). Simulation parameters were chosen from the domain of values usually used in experimental researches, namely: 4 kV voltage and capacity of 200 μF, which gives energy of 1.6 kJ. The peak current through the coil was I_{max} = 28,775 A.
In this case, the specimen was considered of aluminium alloy, EN AW-3105 (AlMn0.5Mg0.5) grade, with 110 mm diameter and 0.43 mm thickness. To show the simulation results, we selected images of the magnetic pressure vectors distribution on the surface of the disk specimen, correspondently to the transitory evolution of the magnetic field, for three time values during the first half period (70 μs).
It is noticeable in Figure 4 that the materials, from which elements of electromagnetic forming device are made, influence both the distribution mode on specimen's surface and the evolution in time of the deformation pressure. On the left column, the corresponding images of the real device (case 1) that contains metallic elements (steel) were placed, and on the right column the virtual device (case 2) composed only of non-metallic elements (polyamide) was represented.
Also, after visualising the action way of the deformation pressure vectors, which actually represent the axial magnetic pressure vectors, under the FLUX2D software

possibilities, studies were made on total magnetic pressure. These studies have followed the amplitude of pressure assessment, as well as the manner that it is modified in the process. For the same parameters used in magnetic pressure vectors simulation, considering an electromagnetic forming device made integrally from polyamide (case 2), the deformation pressure spectre that acts on the workpiece at electromagnetic forming was determined, results being shown in Figure 5.
For the mentioned reasons, related to the small thickness (0.43 mm) of the specimen used in simulation, the enlargement on portions of the specimen's section was necessary, at a convenient scale.

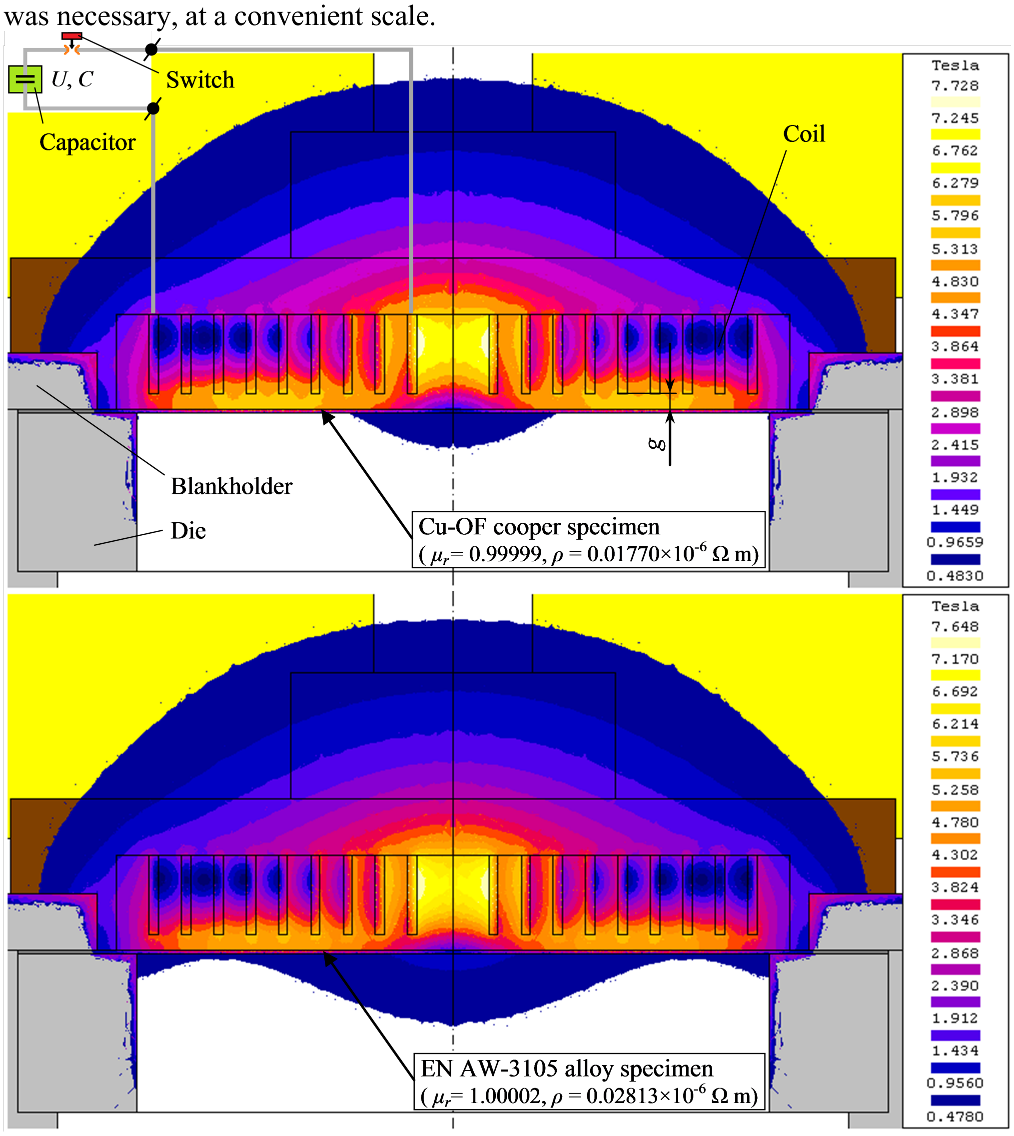

Fig. 2. Simulation of magnetic induction for the cooper (a) and aluminium alloy (b). Simulation parameters: U = 4 kV; C = 200 μF; I_{max} = 28,775 A; g = 2 mm; μ_r - magnetic permeability; ρ - electrical resistivity.

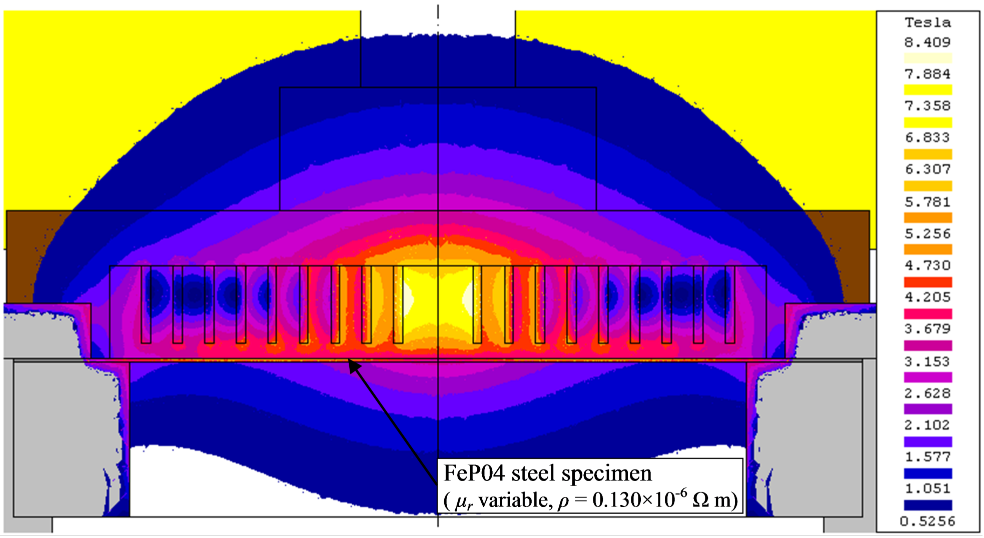

Fig. 3. Simulation of magnetic induction for the steel specimen used in experiments. Simulation parameters: $U = 4$ kV; $C = 200$ μF; $I_{max} = 28{,}775$ A; $g = 2$ mm; μ_r - magnetic permeability; ρ - electrical resistivity.

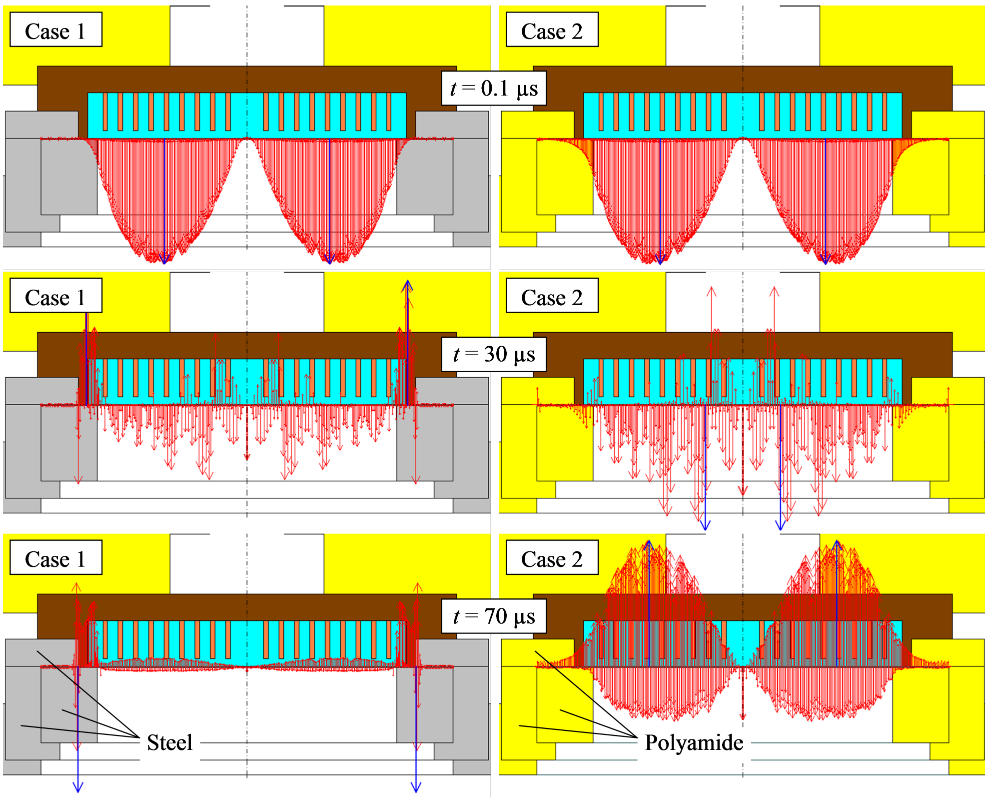

Fig. 4. Magnetic pressure vectors on specimen surface at certain moments of time during the first half period of oscillation of the magnetic field.

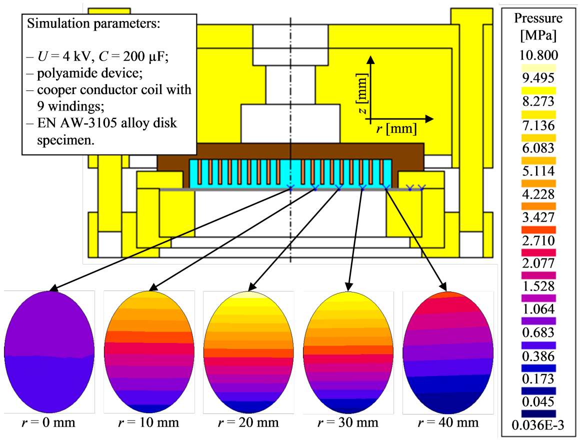

Fig. 5. Deformation pressure variation in the specimen's section, subjected to electromagnetic forming.

The simulations with finite element made for studying magnetic induction and deformation pressure, created in the plastic deformation zone from electromagnetic forming devices, offer unique images on the spatial and temporal distribution of the magnetic induction and deformation pressure.

4. Conclusions

Magnetic induction visualisation (see Figures 2 and 3) shows that in the same device and for the same work parameters (U = 4 kV, C = 200 µF, I_{max}= 28,775 A) different magnetic induction spectres are obtained, because of the different nature materials (workpieces) that are plastically deformed.
Magnetic (permeability, μ_r) and electrical (resistivity, ρ) properties of the workpieces' materials influence not only the skin depth of the magnetic field (as it is known), but also the maximum value of the induction obtained. To be observed that there is no linear dependency between the skin depth and the maximum value of the magnetic induction created.
For steel workpieces' electromagnetic forming special measures should be taken, because in addition to the increased strength at deformation there is also the unfavourable skin depth action, which is much larger than the aluminium and copper.
The materials that the elements of the electromagnetic forming device are made of influence the spatial distribution and the temporal evolution of the deformation pressure. Thus, at a device with metallic and non-metallic elements (case 1) and at one integrally with non-metallic elements (case 2) visible differences appear concerning the action mode of the axial pressure vectors (see Figure 4). The fact that the orientation of the pressure vectors, in case 2, towards the workpiece is longer suggests that greater deformations with non-metallic devices can be obtained.
Images regarding the total pressure spectrum into a plan-meridian section through

the workpiece (see Figure 5), show great variations both on radial direction, as well as on axial direction and indicate the zones from where the workpiece's plastic deformation starts, correspondently to the maximum values of pressure.
Using the results of the electromagnetic field simulation, the electromagnetic forming devices can be optimized to achieve maximum magnetic induction and deformation pressure on the workpiece.

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