Direction Change of the Force Action upon Conductor under Frequency Variation of the Acting Magnetic Field

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Abstract

The present work is dedicated to the description of the thin-walled conductor attraction effect by the pulse magnetic field. This phenomenon was displayed experimentally. The effect pointed out relates to the direction of the pulse magnetic fields energy practical usage for the different technologies in manufacture. In the scientific literature this direction is known as the magnetic pulse metal forming.

A hypothesis about the physical essence of the displayed phenomenon is suggested.

Keywords:

Magnetic fields, Thin-walled metals, Force action

The present work is dedicated to the description of the thin-walled conductor attraction effect by the pulse magnetic field. This phenomenon was displayed experimentally. The effect pointed out relates to the direction of the pulse magnetic fields energy practical usage for the different technologies in manufacture. In the scientific literature this direction is known as the magnetic pulse metal forming or working (MPMF) [1].

The most effective use of MPMF was fixed for the technological processes where the massive conducting objects were subjected to the force action in accordance with the ordered production operation. Their working out was fulfilled in the skin-effect regime which can be realized practically for high frequencies of the acting fields. The resulting forces act as a pressure between the workpiece to be formed and the field source – a coil inductor.

During experimental work with the force action of the pulsed magnetic fields upon thin-walled metals a drawing effect between workpiece and coil inductor could be achieved by decreasing the working frequency below some defined values in conjunction with the electrical, physical and geometrical properties of the workpieces.

Formally, the skin effect regime which is responsible for this drawing effect can be described by the inequality:

$$\omega \cdot \mu_0 \cdot \gamma \cdot d^2 << 1 \qquad (1)$$

where ω is the cyclic frequency of the acting magnetic field, μ_0 is the vacuum permeability, γ and d are the specific conductivity and thickness of the metal.
A scheme of the experiment is represented on Figure 1.

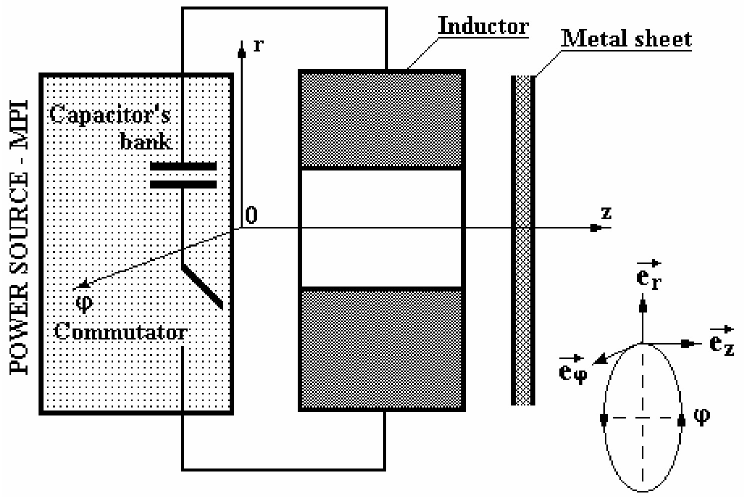
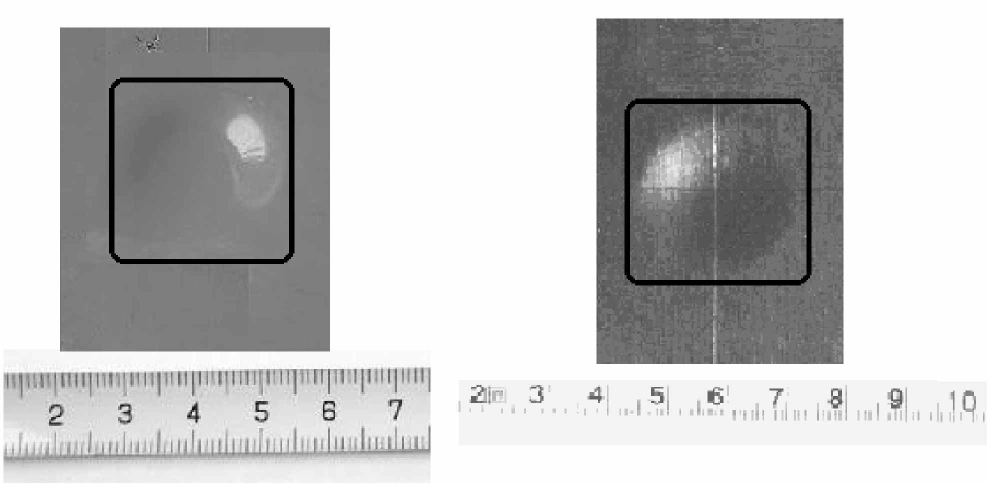


Figure 1: *A scheme of the experiment*

Some steel plates with a thickness of ~ *0.5 mm* were taken as experimental samples. The generators of the magnetic field were the single turn solenoid inductors which were connected to the source with a stored energy of ~ *10 kJ*.

Under frequency of ~ *2.2 kHz* the force action from the magnetic field led to an attraction of the steel sample part and to the creation of the dent according to the cross dimensions of the inductor working zone. An according experimental specimen is represented in Figure 2a.

Under increasing the working frequency up to ~ *7.5 kHz* the same part of the steel plate experienced repelling. A convexity creation takes place, that is an result of the known effect of the magnetic pressure upon the conductor. Figure 2b illustrates the result of this experiment.



a) b)

Figure 2*: Experimental specimen*

A probable hypothesis about the nature of the displayed phenomenon can be based on the following statements.

In the skin-effect regime the pressure upon the plane conductor with the thickness d is caused exclusively by the difference of the squares of the tangential component of the magnetic field strength at the workpiece surface ($H_r(t,r,0)$ and $H_r(t,r,d)$, accordingly to the cylindrical coordinate system in Figure 1) [1]:

$$P_z(t,r) = \frac{\mu_0}{2} \cdot \left(H_r^2(t,r,0) - H_r^2(t,r,d) \right) \tag{2}$$

This formula is always reliable when the normal component of the magnetic field intensity vector is absent. Otherwise additional correspondent force vector components appear. Let us try to point out a possible reason for its appearance.

If the inductor system in Figure.1 has an axial symmetry, the induced azimuthal current density and the electrical field intensity (j_φ and E_φ) as well as the radial and normal components of the magnetic field intensity (H_r and H_z) will appear in the sheet metal.
The Maxwell equation for the current density are:

$$\frac{\partial H_r(t,r,z)}{\partial z} - \frac{\partial H_z(t,r,z)}{\partial r} = j_\varphi(t,r,z) \tag{3}$$

where $j_\varphi(t,r,z) = \gamma \cdot E_\varphi(t,r,z)$; ε_0 - is the vacuum permittivity.

As it can be seen in the equation (3) the induced current density is the difference of the particular derivatives that is two components with different signs. Physical contents may be given to these components: each of them represents a current density caused by the according component of the magnetic field vector. Connecting to_the conductor surface these are the tangential and normal components of the field intensity.

The components of the integral induced current have opposite directions. Dependent on the level of each of them the integral current (induced into the sheet metal) can have one or the other direction. The direction change of the induced current means the change of sign of the vector product in the Lorenz force expression and finally the ponder-motor forces being excited direction change.

Thus, the magnetic pulse field action upon the conductor can lead to the known repulsive forces as well as to the magnetic attractive forces. Obviously for well conductor working in skin-effect regime the attractive force will be very small due to the very small normal component of the magnetic field intensity (on the surface of the ideal conductor it would be exactly zero). But in the case of very thin-walled workpieces this component of the field vector becomes very essential according to an intensive diffusion of the magnetic field through the workpiece wall. The first component of the induced current decreases, but the second one increases here. For the some conditions their difference in the Maxwell equation may change its sign and action of the attraction forces (as it was pointed out!) becomes excelling. The sheet metal will be attracted to the magnetic pulse field source. These statements may be illustrated by some formulas.

The normal component of the distributed ponder-motor force -$P_z(t,r)$ acting upon the conductor with the thickness d if to take in account the vector's product sign will be equaled in the received coordinate system:

$$P_z(t,r) = -\mu_0 \cdot \int_0^d \left[j_\varphi(t,r,z) \times H_r(t,r,z) \right] dz = -\mu_0 \cdot \gamma \cdot \int_0^d \left[E_\varphi(t,r,z) \times H_r(t,r,z) \right] dz \tag{4}$$

To pick out in (4) an addendum according to the magnetic pressure (2) let us substitute expression (3) for $j_\varphi(t,r,z)$ in (4).
We shall get after necessary identical transforming

$$P_z(t,r) = \frac{\mu_0}{2} \cdot \left(H_r^2(t,r,0) - H_r^2(t,r,d) \right) + \mu_0 \cdot \int_0^d \frac{\partial H_z(t,r,z)}{\partial r} \cdot H_r(t,r,z) \cdot dz \tag{5}$$

The comparison of (4) and (2) shows that in addition to the typical force action a second algebraic addendum is being defined in the formula (5). Obviously this component of the excited force defines the attraction of the thin-walled metal by the pulsed magnetic field.

The physical mechanism of the experimentally shown phenomenon should point out that the radial component of the magnetic field intensity does not depend on the longitudinal space coordinate z (the smooth distribution!) under quite low frequency because of the intensive field penetration. And this component derivative along z must be equated to zero. It means that the current density induced in the sheet metal (formula (3)) will be determined exclusively by the derivative of the normal component of the magnetic field intensity along the radius, that is

$$j_\varphi \approx -\frac{\partial H_z}{\partial r} \tag{6}$$

According to expression (5), the ponder-motor force component repelling the sheet metal will be absent. From the magnetic field hand it will experience the action of the attracting forces to the inductor only.
Regarding a finishing discussion of the probable reasons for this attraction effect it should be marked that the suggested physical hypothesis about the displayed phenomenon nature is not the only possible hypothesis. Other explanations are quite probable. For a final conclusion it is necessary to perform more strict theoretical and experimental work, but the known Ampere Low speaks in favor of the suggested hypothesis: As it is known opposite directed currents repel each other (the high frequencies under skin effect). But currents in the same direction attract each other (the low frequency under intensive diffusion of the acting fields). This means that the displayed phenomenon of attraction must be connected with the change of direction of the current induced in the metal which should be deformed.

References

[1] *Batygin Yu.V., Lavinsky V.I.*: The Pulse Magnetic Fields for Progressive Technologies. Kharkov: Publishing House NTU "KhPI". 2001. - 272p. (Russian).