# Detachment of Conductive Coatings by Pulsed Electromagnetic Field


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## Abstract

*The paper presents results of studies on the detachment of conductive coatings from the metal substrate by pulsed electromagnetic field (PEMF). It is known that at the boundary of a metal substrate and an electrically conductive coating having different electrical conductivities sharp changes of PEMF strength arise. This effect has been used to remove a copper layer from a steel substrate. Experimental studies were carried out in the Riga Technical University (Latvia), West Saxony University of Applied Science Zwickau, (Germany) and the Samara Aerospace University (Russia). Generators of pulsed current with power capacity from 1 to 60 kJ with discharge rates from 10 to 100 kHz were used. Treatment of coatings was performed using both flat and cylindrical inductors. The influence of a number of factors on the efficiency of the separation of conductive coating (Cu, Al), such as the thickness and material properties of the coating and substrate, the strength of adhesion of the coating to the substrate, the electrical parameters of the equipment and the inductor system, are shown. Examples demonstrating the main application potential of the method include: deleting of a thin conductive coating induced on metallic and non-metallic products by spraying; separation of layers of metal sheets after their joint rolling or punching; removal of conductive membranes used in the magnetic pulse compression of powders.*



## Keywords

Pulsed electromagnetic field, Conductive coatings, Separation

# 1 Introduction

The method of materials processing by means of a pulsed electromagnetic field (PEMF) has been widely known since early 1970-ths. It is based on the transformation of electrical power, accumulated in a capacitive or inductive storage into a pulse magnetic field (PMF) that performs plastic strain work in a deformed product or accelerating a solid. The theoretical fundamentals of the PMF method were developed in works of G. Knopfel [1], H. Dietz [2], V. Mihailov [3], D. Montgomery [4], R. Winkler [5] and others. In 1980-ths, advances in the practical use of PMF were especially significant for metals deforming. Investigations of that period performed by D. Bauer [6], H. Wolf [7], L. Himenko [8] and V. Gluschenkov [9] are widely known.

From the beginning of 2000-ths, center of the highest activity in the field of PEMF appeared in Germany [10-12], USA [13], China [14], Russia [15] and other countries. Among the most successful technological applications of PEMF the following ones should be mentioned: crimping of tubes made of aluminum and copper alloys, forming shells, calibration of tubular blanks, performing of separation and assembly operations. A large number of publications were devoted to application of PEMF for compression and deformation of powder materials [16-18].

The present work considers some features of REMF use for detachment of electrically conductive coating from the base. Frequently, such detachment presents a rather complicated task. The difficulty is caused by to strong adhesion between the coating and the base, a tiny thickness of the coating, a necessity to preserve both the coating and the base undamaged and by other factors. PEMF can be an effective tool in fabrication of metallic foils, separation of metal sheets, removal of technological shells and membranes, and etc.

The simplest approach is realized by the pulsed electro-dynamic method, where interaction of parallel pulsed currents flowing simultaneously in the coating and basic substrate are used. However, achievement of qualitative exfoliation of coatings is complicated in practice due to the non-uniformity of currents upon the cross-sections of layers, as well as possible melting of the coating. The PEMF method based on influence on the conductive coating by a flat or cylindrical inductor seems more realistic.

# 2 Experiments

Experimental studies were carried out using two layouts of PEMF application to the objects: a) impact by penetrating field with positioning the inductor at the substrate side (Fig.1A) and b) attraction method, where the inductor is located at the coating side (Fig.1B).

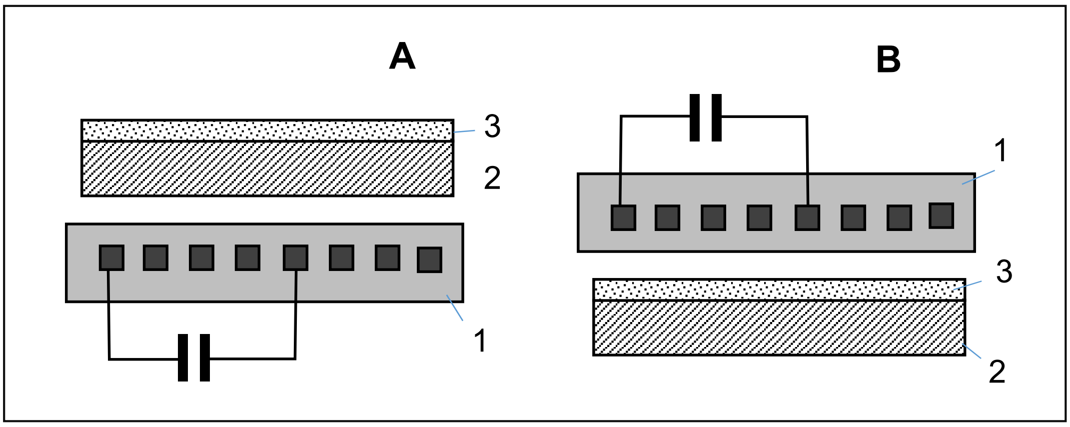


***Figure 1****: Experiment layouts according to penetrating PEMF method with the inductor positioned at the substrate side (A) and attraction method with inductor at the coating side (B). 1 – PEMF inductor; 2 – substrate; 3 – coating*

The experiments were carried out, partially, on the specially designed pulsed magnetic equipment MIU-15 (Fig.2), parameters of which are given in Table 1. Both flat and cylindrical inductors were used.

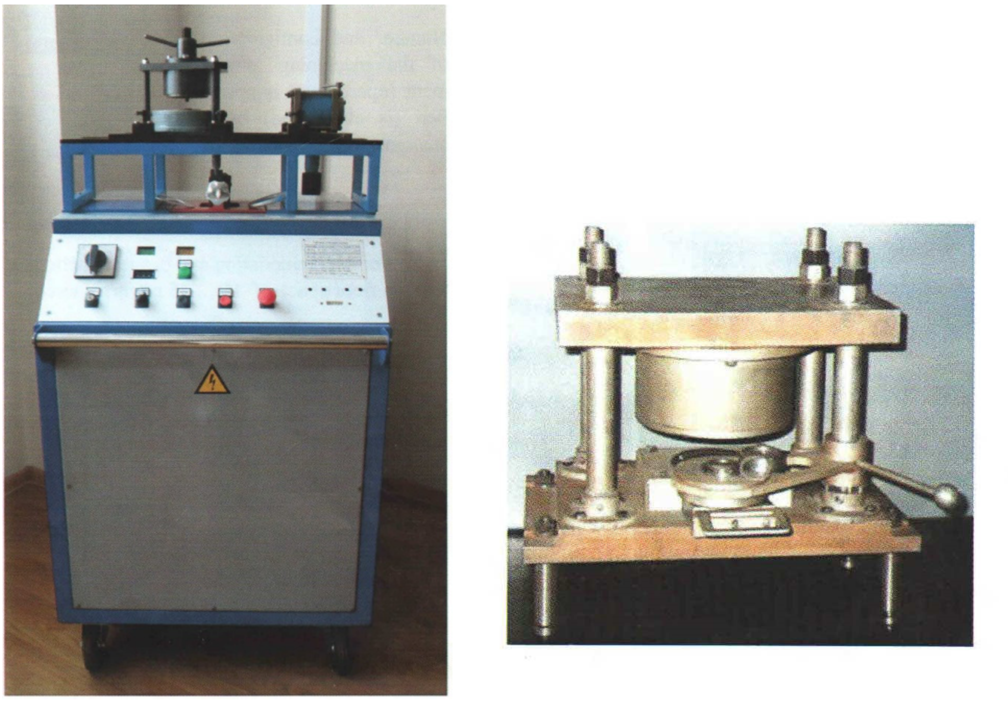

***Figure 2****: Pulsed electromagnetic equipment MIU-15 (left) and inductor arrangement (right)*

| Model | Energy max., kJ | Voltage range, kV | Frequency limit, kHz | Case size (inches) | Weight (lbs) |
|---|---|---|---|---|---|
| MIU-50 | 50 | 5 - 20 | 40 | 61x53x69 | 2640 |
| MIU-15 | 18 | 1 - 20 | 55 | 45x28x61 | 1100 |
| MIU-10 | 10 | 1 - 10 | 55 | 33x37x49 | 770 |
| MIU-3 | 5 | 1 - 6 | 33 | 25x29x32 | 220 |
| MIU-1 | 1,25 | 1 - 7,5 | 70 | 26x15x20 | 110 |

***Table 1**: Main parameters of equipment line MIU used in experiments*

# 3 Methodology

When PMF of a certain intensity is exposed on a metal coating, electromagnetic field $H_2$ produced by eddy currents $i_2$ is induced in its conductive layer. Interaction of eddy currents with electromagnetic field $H_1$ from the inductor results in forces $F_2$ acting on the coating with area $S_2$.

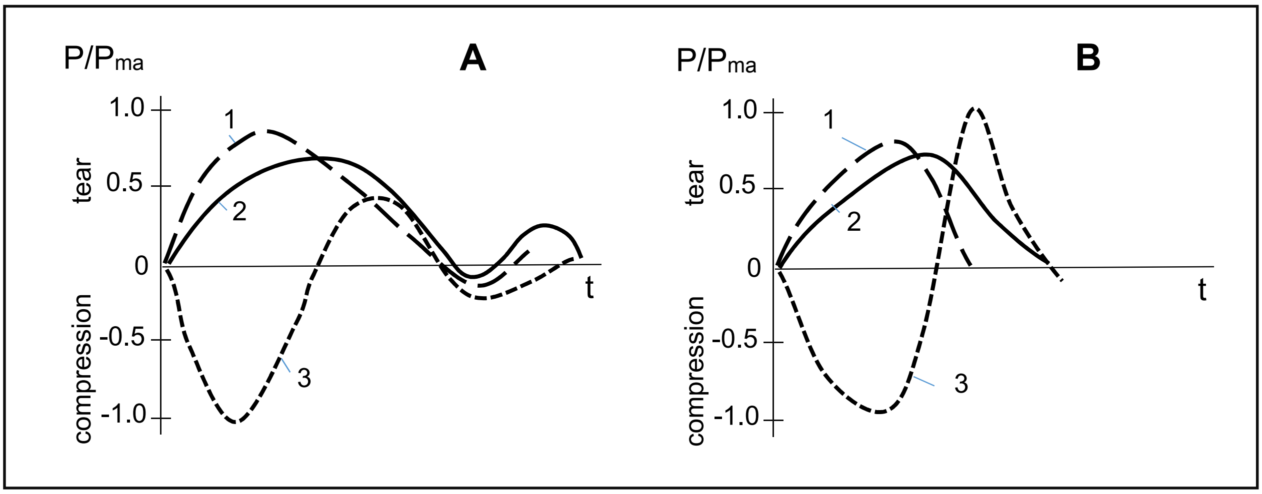


***Figure 3**: Changes of magnetic induction on external (1) and internal (2) sides of steel substrate and pressure of PMF (3) onto coating in the cases of: A - penetrating field according to Fig.1A; B – attraction according to Fig.1B.*

In the case of the layout depicted in Fig.1A (penetrating PEMF), pressure $p_2$ onto the coating is determined by intensity $H_1$ of the fast growing PMF and the degree of its damping by passing through the basic substrate that is characterized by the field attenuation coefficient $K_c$. Pressure $p_2$ is expressed as

$$p_2 = \mu_0 H_1 K_c, \tag{1}$$

where $\mu_0$ is the magnetic constant.

The value of $K_c$ is a complex function dependent on the parameters of discharging circuit (generator-inductor) and the materials and thicknesses of the base and the coating. In this case, the thinner is the base and the lower is its electrical conductivity, the smaller is attenuation of the field. The attenuation effect is absent at all, if the base is made of non-metal material. Changes of magnetic induction on external and internal sides of steel substrate and pressure of PMF onto the coating in the case of penetrating field are shown in Fig.3A.

For realization of the layout of direct impact of PMF according to Fig.1B, it is necessary to create slow increasing PMF in the coating and then to decrease the external field of the inductor with high speed (Fig.3B). A rising electro-dynamic force pulls the coating towards the inductor, causing its detachment from the base. The coating is detached more easily, if the adhesion strength $\sigma_c$ between the coating and the base is lower.

Such a method can be realized by using a “crowbar” system in the PEMF arrangement. The main criterion of the process efficacy is the quality of the detached coating, first of all absence of damages and defects of surfaces of the coating and base. In the process of the coating removal, duration and strength of PMF, the electrical and mechanical properties of the coating and base materials, as well as the adhesion strength of the coating to the substrate, are the most significant.

# 4 Results and Discussion

## 4.1 Process of Separation of Metal Layers

At joint press forming of multiple layers of metals, their grip due to adhesion, formation of burrs and other factors is observed. For comparison, separation of the layers was performed by two PEMF methods discussed above in section 3.

The process of detachment is more technological in the case of “attraction” method, when PEMF is imposed to the coating directly from the inductor as depicted in Fig.1B, and thus it may be implemented directly on the conveyor line. Separation process is particularly effective for coating with high conductivity and using bases made of steel (Fig.4). However, this requires high discharge frequency (above 50 kHz for a copper coating) and, therefore, increases the voltage level of the equipment (10 kV). All this has a significant impact on the longevity of the inductor. In addition, damage was observed on the surface of the detached coating.

***Figure 4****: Example of detachment of copper coating (thickness 0.1 mm) from stainless steel base (thickness 1.1 mm): A – separated base and coating; B – macrostructure of coating surface*

If penetrating field is imposed to the coating from the base side (Fig.1B), the process is carried out under reduced discharge voltage (1 kV) and lower frequency (below 30 kHz). This method is effective in the case of a small thickness of the base (3-5 mm) and its low conductivity. The best effect was achieved by using of stainless steel or textolite as the base materials.

The separation of "stuck" thin walled copper foil and a steel base after stamping operation was conducted by means of a flat inductor and a PEMF equipment MIU. A billet was put in the active zone of a coil inductor (Fig.5). PEMF in this case was directed orthogonally to the coating surface.

***Figure 5****: Inductor's arrangement for separation of metal layers.*

The MIU parameters were: accumulated energy – up to 1kJ; charge voltage – 1…7 kV; natural frequency – 80 kHz. The spiral coil inductor has 12 turns with sizes: ID = 20 mm, OD= 600 mm, inductance – 5.3 µH. Separation of metal layers in the billet of a diameter of 30 mm was performed when the power of MIU reached 100 – 500 J. In some cases, deformation of the copper foil occurred in its plane. It is explained by the non-uniformity of PEMF distribution upon the cross section of the inductor due to the "fossa" or the inactive zone in the center of the inductor's coil.

To record the separation process visually, a highspeed - thermo - camera FLIR SC7300 was applied (Fig.6).

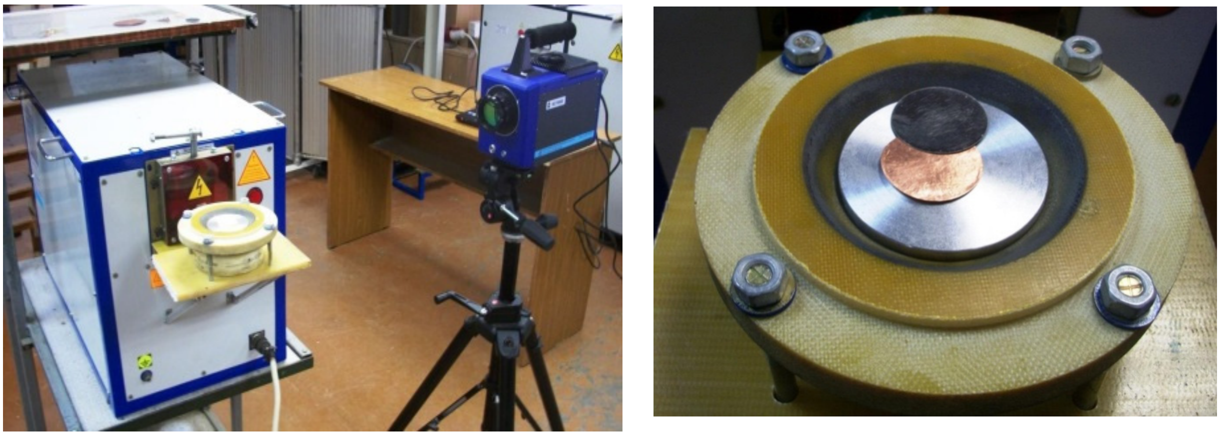

***Figure 6****: Recording of separation mechanism of thin layers in PEMF: setup and billet positioned in inductor.*

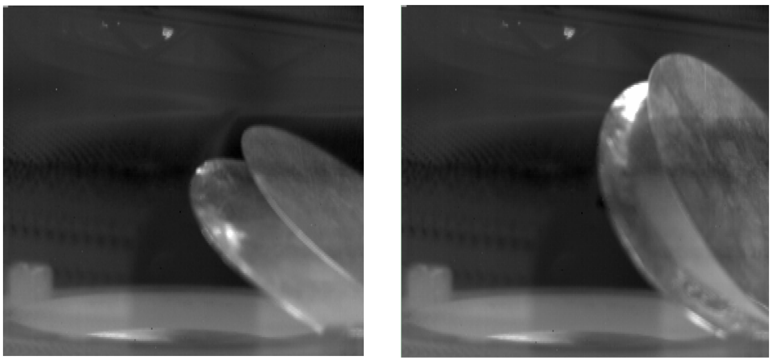

***Figure** 7: Example of recording of separation of copper foil and steel plate.*

Fig. 7 illustrates snapshots of separation of a copper foil from a steel plate of 65 mm diameter. The time-interval between frames was 8 milliseconds.

## 4.2 Process of Removal of Deposited Coating

In this experimental study, the method of separating of a thin foil (Cu-Ni) from steel substrates was used. The foil coating was obtained by vacuum sputtering. The coating was exposed to PEMF from the inductor's side (Fig.1A). Detachment of the coating layer was produced by single pulses using the equipment MIU-15 with above mentioned parameter. A removal case is shown in Fig.8.

## 4.3 Removal of Technological Casing

In the pulsed magnetic compression of powdered materials, technological casing made of materials with a high electrical conductivity (copper, aluminum) are used.

To remove the casing after pressing sleeves of 40 mm in diameter, PEMF method with an inductor positioned in the annular cavity of the preform was used. The method allowed removal of the tubular and annular casings made of Cu without damage that made possible to reuse them. To increase the efficiency, additional measures may be undertaken, such as pre-coating the inner surface of the casing before PEMF by a separating layer of paraffin.

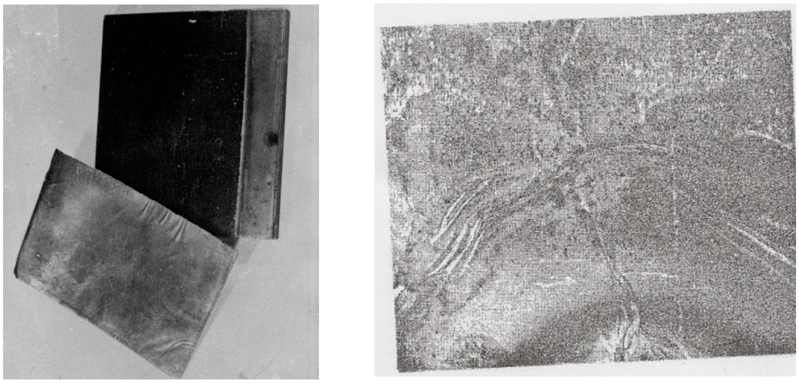

***Figure 8**: Example of removal of Cu-Ni coating (thickness 0.15 mm) from stainless steel base (thickness 1.1 mm) by direct impact on the coating with discharge current above 1kA: A – separated base and coating; B – macrostructure of coating surface*

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