Generation of mechanical vibrations in metal samples by the use of the pinch effect

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Abstract. The article presents the recent research in electrodynamic processes for metal samples exposed to current pulses. The pinch effect and the skin effect cause the vibration of the metal rods. The results of these studies show how current and magnetic field interact with material samples of gold, silver and copper. The analysis allowed establishing the dependences of peak acceleration on current density and conductor diameter. The dependencies can be used in metal workings and for nondestructive testing.

1. Introduction

The influence of large pulse currents on the mechanical condition of metal samples, leading to the disintegration of the conductor to the number of fragments has been described over fifty years ago [1]. To a large extent, such processes involve the interaction of the current-carrying conductor with its own magnetic field and with considerable mechanical stresses generated concurrently [2]. The static forces exertion on the sample material may be described as the influence of the pinch effect [3-5]. Change of mechanical properties during the metalwork caused by current became known as electro-elasticity phenomenon [3]. In recent years a number of research papers has been published studying the changes of the properties of metal conductors caused by transmitting pulse currents through them [6-10]. The authors offer different descriptions of the physical processes occurring in metal samples under the influence of pulsed currents.

2. Physical processes in the conductor carrying the pulse current

Transmission of the current pulse though conductor is accompanied by electromagnetic effect, as well as heating effect. In order to reduce the influence of temperature changes due to the metal heating during the experiments it is preferable to reduce the duration of the current pulse. However, with short pulses of current in the conductor the influence of the skin effect also becomes significant. In these conditions it is not the value of magnetic induction that is important, but the time derivative of it. The change in the magnetic field causes the current distribution in the surface layer of the conductor. This does not imply the absence of heat generation in the fields of electric current. The destruction of thin wires when exposed to short pulses was examined in [6]. The released heat may cause significant dynamic loads. The authors note that such current may cause an explosive destruction of the skin layer of the conductor.

The transmission of pulse current can also lead to a change in the phase composition of the conductor material [7], which is accompanied by its deformation. The combined effect of static load and pulse current can also be accompanied by structural changes in the material [8].

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Since the deformation of the samples occurs at a relatively low heat generation and relatively small currents, mechanical deformations may be caused by forces of electromagnetic field. The research papers [9-11] examine the mechanical impact of the intrinsic magnetic field on the sample carrying the pulse current. The authors establish that mechanical vibrations of the sample are concurrently determined by magnetohydrodynamic processes. It is of interest to consider the features of the accompanying processes.

3. The method of experiments

Pulse current was passed through cylindrical samples of various metals (gold, silver, copper) with different diameters. The experimental setup is shown in Figure 1. In order to reduce the thermal effect the current pulses had a short duration - about 150 microseconds. Varying the amount of current was possible by changing the voltage. The transmission of current was controlled by a magnetic field sensor MLX90242ESE-GDA-000. In order to manage the sensitivity, the distance between the sensor and the sample was chosen to equal 4 mm. Before conducting the test the magnetic field detector was calibrated by transmitting standard current pulses. Characteristics of the magnetic field sensor provides linearity no worse than 1% in the range of magnetic induction of ±0,15 mT

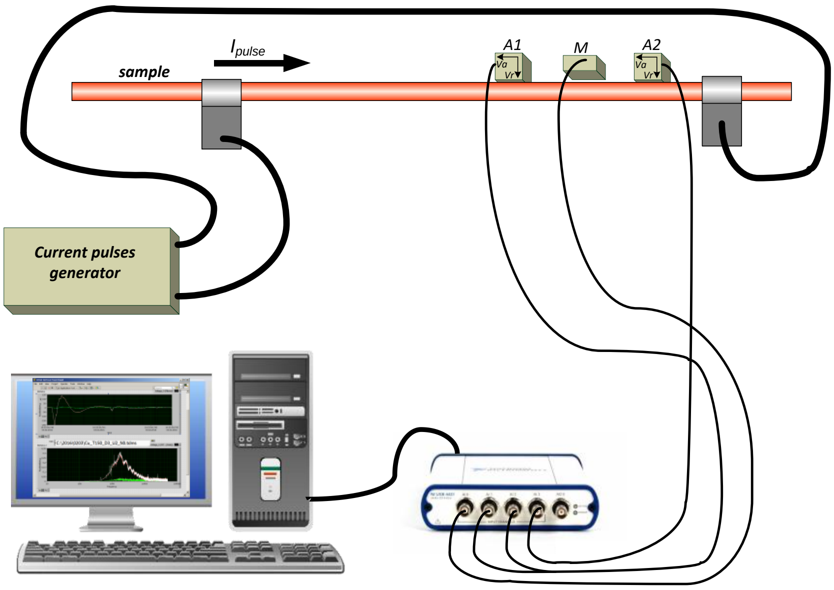

Figure 1. The structure of the measuring stand.

Control of vibration during the transmission of current pulse was carried by three-component piezoelectric accelerometers AP20 of small size and weight. Such accelerometers allow controlling vibration signals in the band up to 40 kHz. Collecting and processing of measurement data was conducted by analog signal acquisition unit 4431 NI USB and by software complex LabVIEW [12].

4. Results of the experiments

The silver samples had the lowest inherent resistance, which allowed setting the amplitude of passed current in the widest range. Assessment of the radical acceleration values characterizing the dynamic forces on the surface of the samples shows a relation close to a quadratic, a typical manifestation of the pinch effect in metals. The corresponding graph is shown in Figure 2.

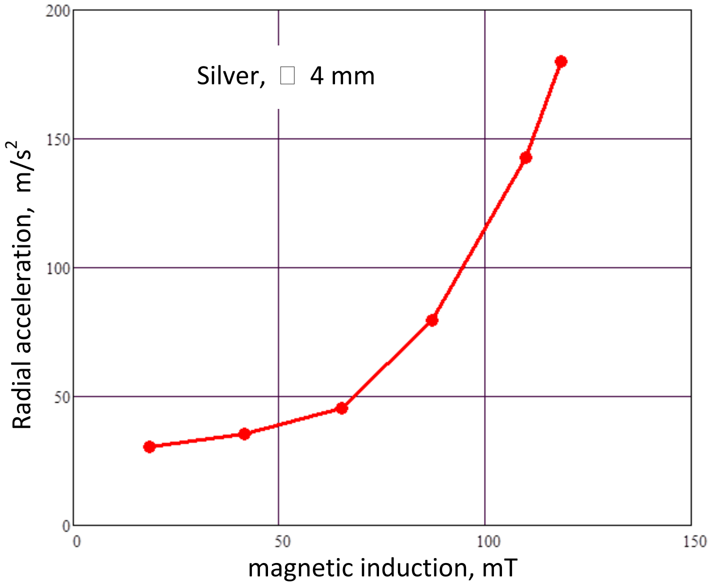

Figure 2. Correlation between radical acceleration and magnetic induction value. Silver sample, 4 mm in diameter.

The response of the sample to the transmission of the current pulse can be divided into two stages. In the first stage, during the current pulse transmission the excitation of deformations and redistribution of current occurs under the influence of change in the magnetic field generated by the current. During the second stage there are dampening intrinsic vibrations in the sample. Such vibrations may be used for providing nondestructive testing [13].

To analyze the processes occurring during pulse current transmission it is most interesting to measure extensively the signals in the first time stage, during the action of the magnetic field. Figure 3. shows the dependence of the magnetic field and the changes of vibration on time. The acceleration of the surface layers of the sample reaches the highest values in the beginning and in the end of the action of pulse current.

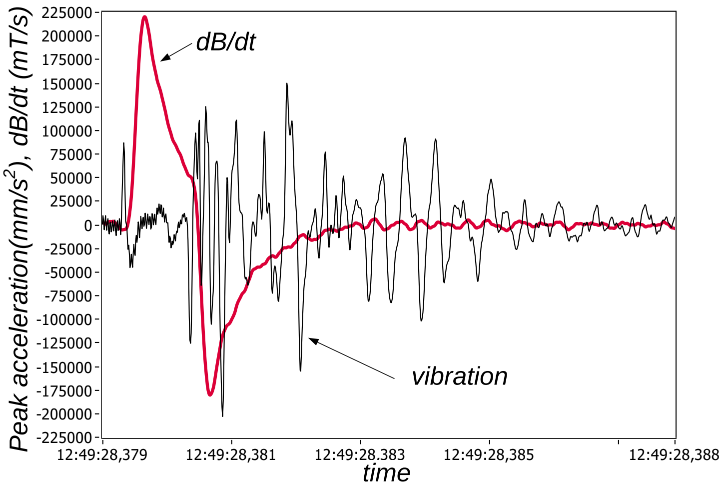

Figure 3. Simultaneous recording of the derivative of the magnetic induction and peak acceleration V2r.

The assessment of the displacement of surface layers is obtained by double integration of the acceleration signals in the axial and radial direction. It should be noted that different signals from different directions of various vibration sensors at the stage of active action of current are characterized by correlation (correlation coefficient more than 0.8). At the same time, the signals from the same direction and various sensors are poorly correlated (correlation coefficient of less than 0.3). This is also confirmed by the form of signals shown in Figures 4 and 5.

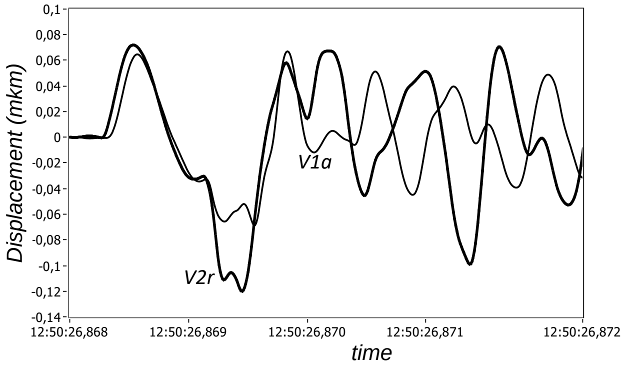

Figure 4. Simultaneous recording of axial vibration measured by a first *accelerometer* V1a and of radial vibration measured by a second accelerometer V2r.

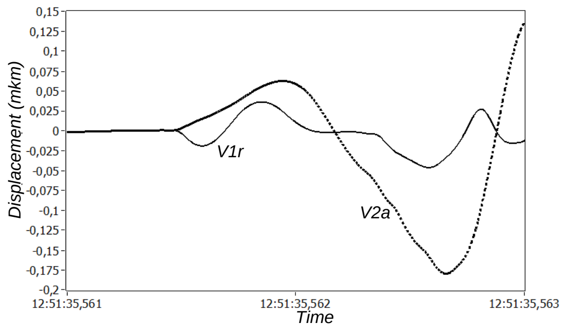

Figure 5. Simultaneous recording. Simultaneous recording of accelerations during the active action of the current pulse.

Such dependences may be regarded as a confirmation of the turbulent nature of MHD processes which cause mechanical vibrations during transmission of pulse current.

Figures 6 and 7 show the dependence of the peak value of the acceleration on the peak current value for silver and gold samples of different diameters. With an equal current finer samples experience larger vibration, i.e. they are impacted by larger dynamic forces. It should be noted that respective dependencies on the value of current density show the inverse correlation. The pulses of equal current density in samples of larger diameter experience vibration of larger amplitude. Corresponding dependencies are shown in Figure 8.

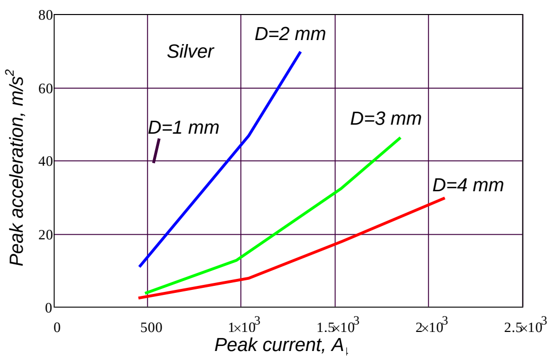

Figure 6. Dependency of peak acceleration on peak current for silver samples of different diameters.

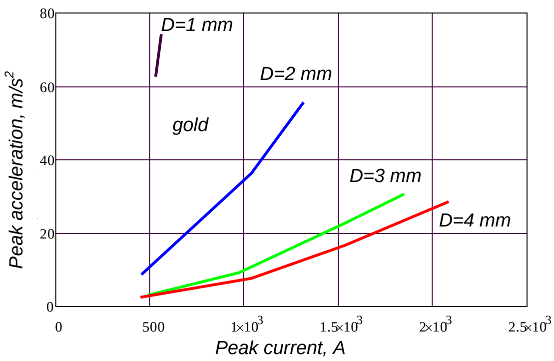

Figure 7. Dependency of peak acceleration on peak current for gold sampled of different diameters.

5. Analysis of the results

Results of experimental studies can be considered as confirming the model of the MHD interaction of pulse current in a conductor with its intrinsic magnetic field [11,14,15]. This applies to the time interval of the active exposure of the current pulse. After the action of the pulse the damped spatial vibrations correspond to the intrinsic vibrations of the fixed sample. With constant amplitude of the pulse current the peak value of vibration response is greater for the samples of smaller diameter, and for materials with a higher specific density. At the constant amplitude of current density the peak value of acceleration of vibration response is higher for the samples of smaller cross-section diameter.

During the active action of current pulse the peak values of amplitude of vibrational response acceleration are close to the moments of the maximum value of the derivative value of the magnetic field.

Vibrational response for the samples with higher specific density is larger, as shown in Figure 9.

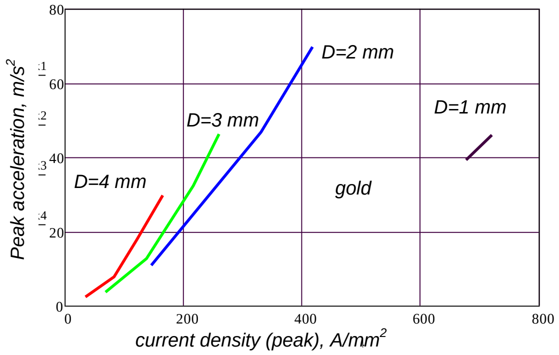

Figure 8. Dependency of peak acceleration value on the peak current density value in samples.

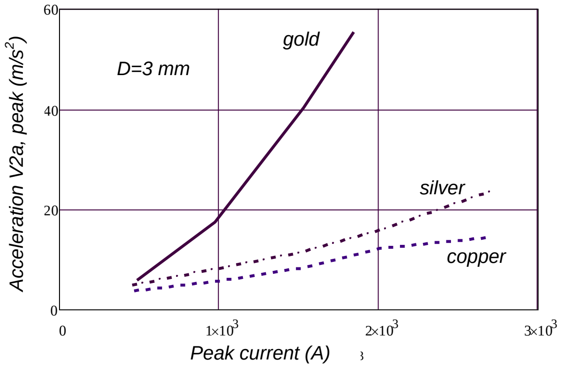

Figure 9. Dependency of peak radial acceleration on peak current transmitted through different samples of 3 mm in diameter.

6. Conclusion

The results indicate the complexity of the mechanism of excitation of mechanical vibrations in metal conductors by passing high-density current pulses. This must be considered in studies on the fatigue resistance of powerful electric equipment elements, in the development of metalwork methods with the use of the current exposure and in non-destructive test systems.

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