Design of mechanical properties of structural materials for power plant equipment

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Abstract. External impulse action on structural materials allows changing their mechanical properties. Such changes occur primarily in the surface layer of the material. One of the simplest methods of such an effect is to apply electrical impulses to metallic materials. Many different hypotheses have been proposed to explain the processes involved. In this paper, experimental data are presented that show that such hypotheses do not satisfactorily explain the observed phenomena. The results obtained show that the description of processes in the surface layer of a metal under the influence of an electric pulse should take into account the observed phenomena. This is the influence of the polarity of the applied electrical signal, the wave characteristics of the generated damped oscillatory processes, the synchronization of such processes with the moments of the beginning of the leading and trailing edges of the applied electrical pulse, the linear nature of the dependence of the amplitude of the vibration response on the amplitude of the applied pulse. The indicated features are manifested both in the region of elastic and plastic deformations of the metal. Such phenomena are observed for samples in the presence of additional static loading, and without it. The need for an adequate understanding of the processes occurring in this case is necessary for the effective application of methods related to the effect of electric pulses on metals. Such solutions are widely used to control the properties of materials in the processing of metals using cutting, drawing, when performing electric-pulse welding and the creation of non-destructive testing at the stages of production, operation and repair of various industrial equipment.

1. Introduction
The mechanical properties of structural materials used in conditions of radiation exposure vary significantly depending on the type of exposure, dose, material used and its processing. This applies to a large extent to materials with magnetic properties [1] and to such elements of electrical equipment as conductive elements. Excitation of vibrations and shock mechanical processes can be used in testing and non-destructive testing of metal conductive elements of power equipment [2]. By setting a high current density through such elements, it is possible to cause not only elastic, but also plastic deformations in them [3]. Elastic deformation in the material of the conductor when transmitting
pulsed currents is manifested in the form of shock or damped oscillatory processes, which can be measured using high-frequency vibration sensors [4].

Significant elastic deformations (units and tens of microns) in the surface layers of conductors when pulsed currents are transmitted have a fusion on the properties of materials. Under such influences, a change in the phase composition and mechanical properties of the material is possible. These features are used, for example, during cold processing in the form of flattening or drawing using the electroplastic effect.

The manifestation of the mechanical action of high-energy electrical processes on the electrically conductive elements of powerful energy equipment is especially noticeable. Although the coefficient of conversion of electrical energy into mechanical energy is relatively small, the concentration of mechanical energy in the surface layers of the conductive structural elements can be achieved at relatively low current densities due to the skin effect. The impact on the surface layer of the material during metal processing improves its structure and uniform distribution of impurities and dislocations, in many cases it increases hardness and other mechanical parameters [5].

The vibroacoustic effect of the pulsed current passing through the conductors allows, in some cases, to replace the temperature and other effects that are difficult to implement in operating conditions of the equipment. In addition, the effect of high-density pulsed currents is accompanied by both mechanical and thermal effects, and the ratio between them can be changed by simple changes in not only the amplitude, but also the duty cycle of the pulses.

Such capabilities of testing [6] and monitoring of metal structural elements can be realized under the conditions of equipment operation, which is important, for example, if there are limitations associated with radiation safety.

Thus, the use of pulsed current influences allows combining the solution of both the problems of diagnosing the condition and processing materials directly on industrial equipment (for example, during repair or after it at the commissioning stage). Moreover, the force action of such pulsed currents allows you to change the properties of the material and reduce the influence of residual stresses [7].

2. Test procedure
The use of a diagram of the dependence of mechanical stresses on predetermined deformations (S-S diagrams) under the influence of electric pulses for studying ongoing processes is widely used. An example of such a dependence is presented in figure 1.

During the action of an electrical impulse, a discharge of the value of mechanical stress is observed. Based on the magnitude of such discharges and on changes in the general form of the dependence, conclusions are drawn about the nature of the physical processes occurring in the test sample.

This technique assumes the presence of additional static loading on the sample. The results obtained take into account only a relatively slow response to the effects of electric pulses due to the low speed of the measuring equipment used in such experiments. In addition, the dynamics of current changes during the action of an electric pulse are usually not taken into account.

To reduce the influence of these restrictions when performing measurements, we used a method for assessing the dependence of the acting mechanical forces and strains based on the measurement of axial and radial components of accelerations and measuring current changes through a sample with an accelerometer and a magnetic induction sensor, as shown in figure 2.
Figure 1. A typical diagram of the dependence of the tensile force on deformation under the influence of electric pulses. Rectangular stainless steel sample. An enlarged scale shows a part of the dependence for two adjacent current pulses.

This technique allows [8] to perform a synchronous analysis of the processes occurring at a high speed. This technique provides measurements, both under the influence of single unipolar electric impulses, and alternating pulses of opposite polarity. In this case, measurements can be carried out, as in the absence or presence of additional external static loads.

Figure 2. An example of an arrangement on a metal sample (1) of length $l$ and diameter $d$ of a multicomponent accelerometer (2) fixed with glue through an insulating gasket, as well as a non-contact magnetic induction sensor (3) under the sample.

3. Experimental data

When studying the vibrational response in samples of various metals (steel, aluminum, copper, brass, titanium, silver, gold) in the form of conductors of rectangular and circular cross section, vibrations in the axial and transverse directions are generated. It was found that the process of excitation of damped oscillations is associated with the formation of short-term processes similar to mechanical shocks at
times corresponding to the beginning of the leading and trailing edges of the applied electric pulse [8]. Such damped oscillatory processes have opposite signs. The resulting oscillations are a superposition of such processes. At the initial moments of the fronts of the electric pulse, abrupt changes in magnetic induction are also observed, followed by a smooth change corresponding to the manifestation of self-induction and skin effect in the conductor.

![Graph](image)

**Figure 3.** Diagrams of magnetic induction (1) and radial vibration (2) of the surface layer of a gold conductor with diameter of 1 mm from the action of neighboring electrical pulses of alternating polarity.

With a change in the direction of the current in the sample, not only a change in the sign of the magnetic induction pulse is observed, but also a change in the sign of the excited oscillations, as shown in figure 3. Moreover, the amplitude of the vibration response both from the results of measuring acceleration and for displacements linearly depends on the amplitudes of the current and magnetic induction, as shown in figure 4. Estimates of the displacement of the surface layers were obtained by double integration of the acceleration signal.

It is essential for understanding the processes that take place at the moment of the onset of the electric pulse that the current is close to zero and, therefore, the currents cannot be the cause of mechanical disturbances in the material of the sample that occur at these moments of time.

### 4. Discussion of the results

The presence of a connection with the polarity of the applied electrical impulses, a linear dependence of the amplitude of the mechanical response on the amplitude of the applied electrical impulse, the manifestation of such a vibrational response under small electrical influences and in the absence of external static loading for conductors made of various metals do not correspond to hypotheses explaining the mechanisms of deformation processes in conditions of electric pulse exposure.
Since the effect of the generation of vibro-acoustic waves in the conductor is present in the absence of external compression or tension for various materials, including in the absence of changes in the structure of the material, changes in this structure cannot be considered as the cause of the resulting deformations. A quantitative analysis of deformation processes under conditions when structural changes are observed in the sample material can show the possible contribution of other mechanisms to these processes. Such additional mechanisms may include the processes described in previously published hypotheses about the mechanisms of electroplasticity.

According to the results of the analysis of the data obtained, we can confirm the conclusion that there is no consistent description of the ongoing physical processes. Such a conclusion is contained both in the papers published in the last century [9, 10] and in the recent papers [11, 12] devoted to this issue.

5. Conclusion
For the effective use of this method of controlling the mechanical properties of the surface layer of metal products already used in products for various purposes, an understanding of the processes taking place is necessary. Such an understanding should be consistent with the obtained experimental data. Such experimental data, obtained both for simple conditions and in the absence of external loads, as well as the influence of temperature effects, contradict the existing hypotheses for describing the mechanisms of electropulse deformation. It is also necessary to conduct additional studies to determine the relationship and synergy of various previously proposed mechanisms under the conditions of creating both elastic and plastic deformations of metals.
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