Onset of Ultrasonic Oscillation at Impulse Processing of Metal Melts

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Abstract. Processing of metal melts powerful electromagnetic impulses - a new and effective way to change the structure and properties of metal. Numerous experiments on ferrous and non-ferrous metals have shown that such processing usually allows both increase in strength and ductility. A theoretical explanation is given to the impact mechanism of powerful electromagnetic impulses on ferrous and non-ferrous metal melts. The possibility to convert electromagnetic impulses to sound waves is shown.

1. Introduction
The results of the numerous experiments on the impact of powerful electromagnetic impulses (EMI) applied to metal melts are shown in the previously published papers [1-3]. The generator used in the experiments has the following characteristics: pulse height – 10KV, duration – 1nsec, repetition rate – 1000Hz. The study of properties and structure of ferrous and nonferrous metals have shown that such processing usually allows both increase in strength and ductility. There are several theories explaining the mechanism of impulse effect on metals. The most promising is the acoustic transformation model, when a powerful electromagnetic impulse is converted into a sound wave in the melt. The same effects as at the ultrasonic treatment are observed. The similarity of effects, produced by the electromagnetic pulse and ultrasonic treatment was shown [6-7].

2. Theoretical study
Let’s consider the process of electromagnetic acoustic transformation (EMAT) in the form of the energy transition from the electromagnetic into the acoustic field [8]. Figure 1 schematically shows the direct EMAT. As it can be seen from figure 1, the nanosecond electromagnetic pulses from the generator output 1 are fed to the radiating inductor 2, which can take any shape and size: removable, pass-through, flat, volumetric, axial or mirror-symmetrical, in the form of a meander or a phased array, etc. The impulses, emitted by the pulses inductor 2, reach the surface of the metal sample 3 and in its surface layer (skin layer) are converted into acoustic-pulses of approximately the same time form and the same duration. The last propagate in the sample in the direction of the radiation, reach its opposite surface, where they are recorded by the receiver, for example, piezoelectric transducer, the electrical signals from which are fed to the input of the nanosecond acoustic impulse registrator (NAI). If the metal sample 3 is placed in the magnetic field, the effectiveness of the direct EMAT increases significantly.
Figure 1. Schematic layout of an arrangement to study the impact mechanism of nanosecond electromagnetic impulses on metals: 1 – EMI generator; 2 – radiating inductors; 3 – metal samples; 4 – acoustic inducer; 5 – NAI registrator.

In the field of practical applications as well as in the scientific research, qualitatively different approaches to the study of EMAT in regular (well conductive weak-magnetic) and magnetically ordered metals has been evolved. The transformation of electromagnetic impulses in the elastic ones due to the Lorentz force is effective under the conditions where the thickness of the skin layer is much less than the spatial length of the elastic impulse as the "smeared" in the space by force is not possible to initiate short-wave elastic impulses. This condition is satisfied in pure metals at frequencies not less than $10^{10}$ Hz and determines the frequency range of the EMAT study. The transformation of electromagnetic impulses in elastic ones due to magnetostriction, in contrast, is effective when this process involves the entire volume of the metal.

If a metal is placed in the constant magnetic field $H_0$, then, the density exerted by the Lorentz force acts on a metal in places, where the density of the current $j$ differs from zero:

$$f^L = \left[ j, H_0 \right]/c.$$  (1)

Besides the Lorentz force there is, however, still the power of a completely different nature. The electromagnetic wave disturbs the equilibrium between electrons and ions. The energy, acquired from the electromagnetic wave, is transferred from electrons to ions as a result of the collision. This results in the emergence of a kind of the force dipole. The importance of this transformation mechanism is the greater the larger is the "leverage" of the dipole – the length of the electron free path.

We assume that the conduction electrons are strongly degenerate gas of charged particles with an arbitrary dispersion law, i.e. the energy of the electron $\epsilon$ and its velocity $v$, generally speaking, are complex periodic functions of the quasi-momentum $p$ ($v = \partial \epsilon/\partial p$). Because of the degeneracy of the electron gas in the EMAT, as in many other "purely metallic-like" phenomena (electrical conductivity, skin-effect, etc.), the decisive role is played by the Fermi-electrons, the electrons at the Fermi surface:

$$\epsilon(p) = \epsilon_F.$$  (2)

The basis of the theoretical study of linear EMAT is a coupled system of linear equations, consisting of elasticity equations and Maxwell's equations. The equations of the theory of the metal elasticity differ from the usual ones by the presence of the right-hand side, containing a force density $D$, which describes the effect of either directly the electric field of an electromagnetic wave, or the conduction electrons on the grid [8].

The analysis of the forces, acting on the metal lattice, shows that the force density $D$ can be represented as a sum of three terms:
\[ \mathbf{D} = \mathbf{f}^L + \mathbf{f}^{ST} + \mathbf{f}^D \]

where, \( \mathbf{f}^L \) is the density of the Lorentz force (3.2); \( \mathbf{f}^{ST} \) – the Stewart-Tolman force

\[ \mathbf{f}^{ST} = -\left( m/e \right) \frac{\partial j}{\partial t}, \]  

emerging because the electrons under the influence of electromagnetic waves move relative to the oscillating crystal lattice, which is a non-inertial system. In (4) \( m \) is a regular electron mass. It occurs only in equations, bound to the inertia force, as the latter does not depend on the periodic field of the crystal lattice [9].

For monochromatic oscillations with angular frequency \( \omega = 2\pi f \):

\[ \mathbf{f}^{ST} = \left( \text{im} \omega / e \right) \mathbf{j}. \]  

The values of \( \mathbf{f}^L \) and \( \mathbf{f}^{ST} \) allow a simple comparison: according to (1) and (5) the Stewart-Tolman force exceeds the Lorentz force if \( \omega > \omega_c = \frac{e \mathbf{H}_0}{mc} \) is the free electron cyclotron frequency. The last term \( \mathbf{f}^D \) is the density of the deformation force.

Maxwell's equations after the elimination of the magnetic field tension of the electromagnetic wave associate the current density \( \mathbf{j} \) and the intension of the transverse part of the electric field \( \mathbf{E} \):

\[ \text{rot} \text{rot} \mathbf{E} = -(4\pi/c^2)\frac{\partial \mathbf{j}}{\partial t}, \text{ div} \mathbf{E} = 0. \]  

The longitudinal component of the electric field \( \mathbf{E} \), if it is not identically equal to zero, is excluded by the condition

\[ \text{div} \mathbf{j} = 0. \]

In general, the current density is determined by the of non-equilibrium correction \( \delta \mathbf{f} = \left( \mathbf{\partial f}_F / \mathbf{\partial e} \right) \chi \)

to the Fermi electron distribution function \( f_F \)

\[ \mathbf{j} = -e \langle v \chi \rangle. \]

Here the angle brackets denote averaging over the Fermi surface. Function \( \chi \) is the solution of the kinetic equation:

\[ \frac{\partial \chi}{\partial t} + v \frac{\partial \chi}{\partial \mathbf{r}} + \frac{e}{c} \left[ \mathbf{v}, \mathbf{H}_0 \right] + \frac{\partial \chi}{\partial \mathbf{p}} + \mathbf{\chi} = -e \mathbf{v} \left( \mathbf{E} + \frac{1}{c} [\mathbf{U}, \mathbf{H}_0] \right) - \frac{m \mathbf{U}}{e} - \Lambda_{ik}(\mathbf{p}) \dot{\mathbf{U}}_{ik} \]

where \( \mathbf{v} \) is the operator of electron collisions. Almost always we will use \( \tau - \)approximation, i.e. \( \chi \)

replace the integral in the \( \mathbf{p} \)-space operator by the \( \mathbf{v} \) relaxation frequency \( v = 1/\tau \), where \( \tau \) is the time of the electron free path.

The right side of the kinetic equation (9) shows that the electronic system is taken out of balance not only by the electric field, but also by the movement of the (ion) metal crystal lattice. The movement of the crystal lattice is manifested in the presence of terms (in the right side of equation (9)), depending on the time derivatives of the vector \( \mathbf{U} \) and tensor \( U_{ik} \). The terms, containing time derivatives \( \dot{\mathbf{U}} \) and \( \ddot{\mathbf{U}} \), are stipulated by the electrons moving along the vibrating lattice: \( e [\dot{\mathbf{U}}, \mathbf{H}_0]/c \) is the Lorentz force acting on the metal ion, \( m \ddot{\mathbf{U}} \) is the Stewart-Tolman force. The last term \( \Lambda_{ik}(\mathbf{p}) \dot{\mathbf{U}}_{ik} \) is the effect of the
direct bond between the electrons and the lattice. \( \lambda_{ik}(p) \) tensor is called the renormalized tensor of the deformation potential:

\[
\lambda_{ik}(p) = \delta \varepsilon(p) / \delta U_{ik}.
\]

Renormalization is the effect of the requirement of the metal quasi-neutrality. The tensor of the deformation potential \( \lambda_{ik}(p) \), describing the bond between the electron and the long-wavelength phonons, that serves as a "phonon charge" of the electrons. This is an analogy between the expressions \( \delta \varepsilon = -e \varphi \) and \( \delta \varepsilon = \lambda_{ik}(p) U_{ik} \), \( \varphi \) is the potential of the electric field, \( U_{ik} \) is the phonon potential. It is necessary to note how the sound wave disturbs the system of electrons from equilibrium: first, creating an electric field \( E \) – the electrochemical potential gradient; secondly, due to the \( U \) and \( U_{ik} \) time dependence. Spatial heterogeneity of these characteristics could lead to non-uniform distribution of electrons in a conductor, but cannot disturb the electron state of equilibrium. The task of the metal spectroscopy is to define tensor \( \lambda_{ik}(p) \) components for various cavities of the Fermi surface and at various points in these cavities. At present the structure (topology, the size of the cavities) of the Fermi surfaces of almost all metals is known with great precision, but the study of the deformation potential tensor is just at its beginning.

The definition applied to \( \lambda_{ik}(p) \) is the deformation potential tensor and it’s not apt enough. The reason is that it describes two different effects: a true change of the electron (its energy) dispersion law stipulated by the elastic deformation of the crystal, and the electron impulse transfer from one point of the crystal to another on account of velocity different from zero. Thus, even at the free electron approximation, when the electron energy does not depend on the capacity of the lattice ions, the tensor \( \lambda_{ik}(p) \) differs from zero and is equal to \( p v_k = m v_k \).

For the free-electron approximation the equation for the "deformation" force is:

\[
f^D = -ne(E \cdot j / \sigma_0),
\]

and allows clear understanding that the deformation force differs from zero only due to the spatial dispersion of conductivity (\( \sigma_0 = ne^2 l / p_e \) is the static conductivity of metal). Therefore, the EMAT occurring due to the deformation force, is favored by the extremely anomalous skin effect \( (1 \gg \delta) \), where \( \delta = c / \omega \) is the depth of the skin-layer), when the difference \( E \cdot j / \sigma_0 \) is at the maximum.

The above equations constitute a system of equations that allows studying the propagation of bound electromagnetic-acoustic oscillations in metals. To receive self-contained, applicable for analysis equations, it is necessary to specify the relation between the parameters (there are a lot of them under such general problem statement). In a strong magnetic field \( (\omega \tau >> 1) \), when weak decaying waves are spread in the electron subsystem of the metal [10], their interaction with sound waves alters significantly the wave properties of the metal.

To consider EMAT from the theoretical standpoint, as stated above, it is necessary to cover inhomogeneous problems. The simplest of them is: an incident electromagnetic wave falls on the metal surface, filling the half-space. This problem statement requires the formulation of boundary conditions. Firstly, these are natural electromagnetic conditions of the equation (6): the continuity of the tangential components of the electric and magnetic fields at the boundaries of the half-space occupied by metal; secondly, the conditions corresponding to a particular character of boundary "securing": if the boundary is free, then elastic stresses are equal to zero, and if it is fixed, then there should be no disposition; thirdly, it is necessary to set the boundary conditions to the equation (9), describing the interaction between conducting electrons and the surface; and finally, fourthly, it is necessary to set the conditions at infinity – deep inside the metal. For EMAT the latter conditions are formulated as the conditions of the electromagnetic field and the displacement field reducing to zero at infinity as well as the non-equilibrium increment to the electron distribution function.
Before proceeding to the solution of specific problems, we should discuss the ways to significantly simplify the problem statement. Only choosing a very specific boundary condition for the function $\chi$, we can achieve significant simplification: either at diffuse scattering of electrons the non-differential part of the nucleus is reduced to zero - you can use the Wiener-Hopf method [11]. Or at specular reflection, expanding in a certain way all the required functions on a metal-free half-space, it is possible to artificially "create" a differential nucleus and with the integration limit from $-\infty$ to $+\infty$, that allows you to apply the Fourier method for the solution of the problem. On the other hand, the study of limiting cases indicated that the change in the boundary conditions for the distribution function of electrons has little effect on the value of the linear response of the metal. Since the bond between electromagnetic and acoustic waves is small, then the problem of EMAT can be divided into two stages. The first stage is the solution of electromagnetic problems: the calculation of the electromagnetic field in the metal. The second stage is the calculation of the force density and the solution of the acoustic problem with the corresponding boundary conditions.

For the half-space the division may not be feasible in cases where weak decaying electromagnetic waves propagate in the metal, placed in a strong magnetic field ($\omega / c \tau >> 1$). If the frequency of the incident electromagnetic wave, falling on the metal, corresponds with the possibility of the resonance between the weak decaying waves and sound, then, it usually becomes necessary to solve electromagnetic and acoustic problems jointly.

During EMAT a geometric resonance is possible on the metal plate of the finite thickness (not on the half-space): an integer of sound half-waves is placed on the metal plate of finite thickness. In this case the calculation of the resonance of the electromagnetic impedance of the plate is more convenient to carry out self-consistently without dividing the task into two stages.

The proposed approach allows to solve the problem of the origin of the acoustic oscillations in the metal due to single-frequency sinusoidal electromagnetic oscillations. Transition to impulse exposure may be performed using Fourier transformation.

EMAT studies in liquid metals were performed by different researchers considering the fact that the transverse elastic waves do not propagate in fluids, and the generation of longitudinal elastic waves is satisfactorily described by the theory of induction interaction. In this case, however, the important role is played by the boundary conditions of the problem. For a free metal boundary the condition for the absence of stress is applied. For the liquid, drenching the walls of the crucible, the assumption of boundary conditions for a fixed surface-mount $u_{z=0}$ is justified.

In this case, the transformation effectiveness

$$W \approx \frac{1}{\rho_M S}, \frac{\beta}{1 + \beta^2} \approx \frac{s \sigma}{\rho_M \omega}. \quad (12)$$

This expression can be compared to EMAT efficiency in the metal free surface, the expression for which can be written as

$$W \approx \frac{1}{\rho_M S}, \frac{1}{1 + \beta^2} \approx \frac{S^2 \sigma^2}{\rho_M \omega^2}. \quad (13)$$

We see that in limit $\beta << 1$ the transformation effectiveness in the case of the fixed surface $\beta$ times exceeds $W$ at the free surface. Due to this reason, the amplitude of longitudinal elastic waves may be significantly increased in the conductive liquid metals with an appropriate choice of frequency.

The calculation of EMAT effectiveness in certain liquid metals, normalized to the effects of EMAT in aluminum at the frequency $f = 10$ MHz at room temperature, is shown in the table 1 (transformation effectiveness in aluminum at room temperature is taken as a unit).

The experiment, carried out on the melts of cesium and mercury, corroborated these calculations. The measurements were carried out using a pulse-echo method with two helical coils for sound generation and recording, or with a coil encompassing the glass crucible with the metal inside.
3. Conclusions

The method of excitation of longitudinal elastic waves in liquid metals as a result of exposure to EMI can be particularly useful at high temperatures, when the problems, associated with acoustic contact and emergence of metal oxides on the metal surface, create considerable difficulties. The same method, apparently, can be used to study phase transitions of liquid-solid body.

In experimental studies on processing EMI aluminum, copper, lead and bismuth were treated. The effects of changes in the properties are seen in all metals. It means that even at low coefficients of transformation (lead and bismuth) energy impulse action is enough to obtain new properties of cast metals.

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