On the question of finding a universal mechanism for the transmission of sound wave energy in iron during heating and deformation

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Abstract. The paper presents a theoretical analysis of the experimental data on the ultrasound speed change in iron during heating and elastic deformation. The mathematical models proposed for assessing the change in the ultrasound speed based on the “adiabatic approximation” method do not explain, using one model, the change in the ultrasound speed in iron during heating and elastic deformation. During theoretical analysis, a new model of ultrasound wave transmission has been proposed, in which the wave energy propagates in the volume of the interatomic bond, namely in the loop, which is formed by the “collectivization” of valence electrons located in the outer orbit of atoms. The new model explains why with an increase in the interatomic distance \(a\), the crystal lattice parameter, and an increase in the natural vibration frequency of atoms \(v_{at}\) during heating and elastic deformation, in one case (heating), the speed of the sound wave decreases, but in the other case (elastic deformation), the speed of the wave increases with a general decrease in the temperature of the rod.

1. Introduction
In his work [1], Academician Ya. I. Frenkel points out: “... physicists often diligently develop a theory in a formal-mathematical direction, taking little interest in the question of to what extent its foundations correspond to reality”. With this expression, Frenkel raises the issue that mathematical models (MM) should reflect all physical processes occurring in the volume of the material, or rather, the processes occurring in the smallest structural unit of the material, namely the primitive cell of the crystal lattice (CL) or processes in atomic planes that form the volume of the primitive cell. Ideal MM should simultaneously evaluate the experimental data obtained under various physical influences, for example, during heating and elastic deformation of the rod, taking into account that the method for assessing internal changes is carried out on the basis of one method, for example, based on the method of molecular acoustics (MA). The choice of this estimation method is due to the fact that the change in the velocity of the ultrasound (US) wave is influenced by the peculiarities of the molecular structure, the forces of interatomic interaction, as well as the packing density of the crystal lattice, which changes under the action of an external load and temperature.
2. Methods

Based on the model of US wave transmission by elastic interaction of shells of atoms, proposed by Ya.I. Frenkel in [1] in [2-6], it was possible from a theoretical point of view to explain the process of changing the US velocity during elastic and plastic deformation of an iron rod. The theoretical analysis was carried out on the basis of the equation

\[ \mathcal{G}_i = l_i \cdot \nu_{at} \cdot \frac{1}{n} \text{ (m/s)} \]  (1)

where \( l_i \) – length of the interatomic bond (the edge of the primitive cell) expressed in terms of the crystal lattice parameter \( a \) – length of the interatomic bond in the atomic plane.

\( \nu_{at} \) – vibration frequency of atoms in the volume of a primitive cell.

\( n \) – number of interatomic bonds used to transfer US energy in the plane and between adjacent parallel atomic planes forming the primitive and “skeleton” of the unit cell of the crystal lattice of the material, which determines the longitudinal, transverse and velocity of ultrasound in the rod based on the parameters of the primitive cell. In this case, the theoretical values of these velocities for iron, BCC crystal lattice, and copper, FCC crystal lattice, coincide with the experimentally established values by the method of molecular acoustics (MA) with a high accuracy of 95-100% [2]. On the basis of equation (1) in work [4], it was also possible to explain the reasons for the sharp decrease in the US rate in iron during the polymorphic transformation of primitive cells from \( \alpha \text{Fe} \) to \( \gamma \text{Fe} \). Based on the principle of uniformity of the process of transmission of sound wave energy in iron during deformation and heating, it is proposed to carry out a theoretical analysis of the correspondence of equation (1) for the process of heating iron.

3. Results and discussion

It is known [7] that when the material is heated, an increase in the amplitude of the atomic vibration - \( A \), occurs, which leads to an increase in the crystal lattice parameter \( a \), which is reflected in the form of an expansion of the volume of the heated material. Thus, in equation (1), the parameter of the interatomic bond length \( l_i \) increases. To determine the change in the natural frequency of vibration of an atom \( \nu_{at} \) in the volume of a primitive cell, we use the law of conservation of the mass of an atom \( m_{at} \) in the changing volume of a primitive cell per unit time:

\[ \frac{m_{at}}{V_i} \cdot \frac{1}{\tau_i} = \text{Const} \]  (2)

where \( V_i \) - the changing volume of a primitive cell considered over a certain period of time \( \tau_i \). Note that this equation (2) in a latent form reflects the condition of continuity of the density of the material under external influence - heating or deformation in accordance with the equation

\[ \frac{m_{at}}{V_{\tau_o}} - \frac{m_{at}}{V_{\tau_1}} = \frac{\rho_{\nu_{\tau_o}}}{\tau_0} - \frac{\rho_{\nu_{\tau_1}}}{\tau_1} = 0 \]  (3)

as a result of which the equation (2) can be extended and represented as:

\[ \frac{m_{at}}{V_i} \cdot \frac{1}{\tau_i} = \rho_{\nu_i} \cdot \frac{1}{\tau_i} = \rho_{\nu_i} \cdot V_i = \text{Const} \]  (4)

The general assessment of equation (4) as well as the relationship of changing values can be obtained using the nomogram shown in figure 1.
Figure 1. Nomogram of the dependence of the change in the physical values of a primitive cell with a change in the volume of a primitive cell.

The second quadrant reflects the hyperbolic law of conservation of the mass of an atom per volume of a primitive cell, which changes depending on external conditions. Thus, with an increase in the volume of a primitive cell to a value $V_1$ upon heating or elastic deformation, the natural vibration frequency of the atom $\nu_{at}$ increases in the first quadrant of the Cartesian coordinate system (an increase in the natural vibration frequency of an atom in the area of elastic deformation was established in [8]). It turns out that in equation (1) the natural frequency of vibration of the atom $\nu_{at}$, as well as the amplitude, increases, which, in accordance with MM of US transmission by deformation of the shells of atoms should lead to an increase in the transmission rate of the ultrasound wave in iron when heated. However, in the experimental works [9-11] it was found that when iron and other metals are heated, a decrease (drop) in the velocity of the ultrasonic wave is observed. Thus, equation (1) based on MM transmission of sound in metal through the elastic interaction of atomic shells does not correspond to the real process occurring in the material during heating, which is most likely due to the fact that this MM based on MM “adiabatic approximation”.

Let us assume that the transmission of the US wave in the heated metal is carried out due to “quasiparticles” (phonons). The phonon energy $E_f$ is associated with the natural vibration frequency of the atom $\nu_{at}$ on the basis of the equation

$$E_f = \hbar \nu_{at}$$

where $\hbar$ - reduced value of Planck’s constant (Const).

$\nu_{at}$ - natural frequency of vibrations of atoms.

The natural frequency of atomic vibration $\nu_{at}$ during heating, an increase in the volume of a primitive cell, increases in accordance with the continuity condition (3), which leads to an increase in the phonon energy, and this, in turn, leads to an increase in the kinetic energy of the phonon.
\[ E_f = \frac{m_f \cdot v_f^2}{2} \]  

\( m_f \) - phonon mass

\( v_f \) - phonon velocity.

That is, the speed of movement of the phonon increases. In accordance with the assumption of the transmission of sound in the metal by phonons, the velocity of the US wave in the metal should increase. However, the experimental data of works [9-11] contradict these conclusions. In general, it should be noted that the phonon is a fictitious particle on what Frenkel pointed out: “Similar fictitious particles, called sound quanta, or phonons, are introduced into the modern theory of thermal motion in solids” [1]. Thus, the MM transmission of sound by a “quasiparticle” also does not correspond to the real process of a decrease in the speed of sound during heating.

If we pay attention to the experimental analysis of changes in the physical parameters of a primitive cell in the area of elastic deformation, we can establish that in metals there is an increase in the natural frequency of vibrations of atoms \( \nu_{at} \) [8] with an increase in the volume of the rod [12], which fully corresponds to the theoretical analysis in accordance with the nomogram of changes in physical parameters see figure 1. Taking into consideration that in CL “normal modes (vibrations) of the crystal lattice can be considered harmonic oscillators” [13], then the energy of a harmonic oscillator (atom) expressed by the equation

\[ E_{at} = \frac{m_{at} \cdot A^2 \cdot \nu_{at}^2}{2} \]  

where \( m_{at} \) - atom mass, \( A \) – atomic vibration amplitude, \( \nu_{at} \) – natural frequency of vibration of an atom. shows that with an increase in the natural frequency of vibrations of atoms \( \nu_{at} \), an increase in the energy of atoms occurs in the entire volume of the deformed rod in the area of elastic deformation. In this case, the US velocity at elastic deformation increases in both BCC crystal lattice and FCC crystal lattice, which is confirmed by experimental works [14-16]. Thus, the first contradiction arises: both processes are characterized by the same changes in the physical parameters of the primitive cell of CL, but the result is diametrically opposite. It should also be noted that the temperature of the iron rod during elastic deformation ... decreases! This decrease in temperature was established experimentally in the works of Joule and A. Nadai on iron samples [12,17]. In this case, a second contradiction arises - the temperature of the iron rod, in the elastic area, decreases with an increase in the natural vibration frequency of the atom and an increase in the internal energy of atoms in the volume of the deformed rod. Nadai explains the change in temperature as follows: “Thus, during adiabatic volumetric expansion (compression) of an elastic liquid or solid, heat is absorbed (released) ...” [12]. However, a solid is not a gas and it is possible to apply the developed model of the adiabatic process for a gas to a metal only if we use the “adiabatic approximation” method. When using this approximation, it is believed that the motion of electrons occurs in the field of stationary nuclei. Thus, in the case of elastic deformation of the rod, as the displacement of atomic nuclei from the equilibrium position, it is possible to assume that the adiabatic process occurs in an “electron gas” [18, 19], which fills the volume of a primitive cell. But then it is necessary to accordingly assume that the sound wave also propagates in CL metal due to the movement of electrons (sound propagates in an electron gas). To determine the speed of sound in an electron gas, as an ideal gas, we use the equation that determines the speed of sound in gases

\[ v = \sqrt{\frac{\gamma \cdot P}{\rho}} = \sqrt{\frac{\gamma \cdot R \cdot T}{\mu}} \]  

where \( \gamma \) - adiabatic index of the gas, \( \rho \) - density of the gas, \( P \) - pressure of the gas, \( R \) - gas constant, \( T \) - temperature of the gas, \( \mu \) - viscosity of the gas.
where $P$ – pressure, $\rho$ – gas density, $\gamma = \frac{C_p}{C_v}$ (ratio of heat capacity at constant pressure to heat capacity at constant volume), $T{^\circ}C$ – gas temperature, $\mu$ – molecular weight of gas, $R$ – universal gas constant.

General analysis of equation (8) shows that the speed of sound $\nu$ in ideal gases does not depend on pressure, but changes proportionally $\sqrt{T{^\circ}C}$. Therefore, with a decrease in $T{^\circ}C$ of an iron rod due to a decrease in the energy of the electron gas in the area of elastic deformation, as an adiabatic process of volume expansion, the speed of sound in the gas should decrease, which, accordingly, should lead to a decrease in the velocity of the US wave in metal. However, in the area of elastic deformation, the velocity of the US wave in metals increases [14-16], which contradicts the assessment of the US velocity in gas based on equation (8).

The next contradiction lies in the fact that in one volume of gas it is impossible to simultaneously carry out two adiabatic processes at once, leading to the appearance of a temperature gradient in this volume of gas. However, in metal volume it was experimentally possible to obtain both processes simultaneously! In his work [12] A. Nadai points out: “If a prismatic rod made of low-carbon steel is instantly loaded in the elastic range by two equal and oppositely directed moments, creating its uniform bending along the length, then the stretched fibers parallel to the axis of the rod will cool slightly, and the compressed - will slightly heat up compared to the initial unloaded state." It turns out that the experience of A. Nadai indicates that the volume of the rod $V_{st}$ consists of smaller volumes belonging to the kinetic units (KU) of the material. Thus, it is impossible to explain the physical processes of changes in sound velocity and the temperature gradient observed during elastic deformation of the rod on the basis of the “electronic” gas that “randomly moves” throughout the volume of the deformable rod.

In fact, on the basis of the “adiabatic approximation”, which divided CL into electron gas and atomic nuclei, it is not possible to explain the change in sound velocity and temperature changes either on the basis of the model of sound transmission through the elastic interaction of atomic shells or on the basis of the model of sound transmission through the “electron gas”. Therefore, it remains to assume that the sound wave energy transmission in metals is carried out as a process of interaction of electrons and atomic nuclei, i.e. sound transmission should be associated with the mechanism of interatomic interaction, for example, on the basis of “collectivization” of electrons in the outer shells of atoms. In [2], a refined model of the “collectivization” of atoms was presented in figure 2, based on the concept of the unification of “magnetic lines of force” given by Academician V.F. Mitkevich in his work [20].

![Figure 2. Unification model of “collectivization” of valence electrons located in the outer orbit of the atom in a magnetic loop $R_{m.l.}$](image)

The union of electrons creates closed “magnetic” loops, through which the contraction of atomic nuclei is carried out [2]. In a loop, which has the shape of a “tunnel”, the mass of each electron has two
velocities (circumferential $\omega$ and longitudinal $v_p$ as in figure 3), which create a vortex motion of the electron in the volume of the loop.

It should be noted that when the mass of the electron $m_e$ moves around the atom, at a certain radius $R_{orb}$, as in figure 4, the electron has a centripetal acceleration $a_{cent}^{orb}$, which creates a force $F_{cent}^{orb}$ that should displace the atom from the equilibrium position.

$$F_{cent}^{orb} = m_e \cdot a_{cent}^{orb} = m_{el} \cdot \frac{v_p^2}{R_{orb}}$$ (9)

Taking into account this mechanism of atom displacement under the action of force $F_{cent}^{orb}$, it can be assumed that “zero vibrations” [7] which cannot be explained on the basis of “thermal motion” correspond precisely to this mechanism of atom vibrations at absolute zero (0° K), taking into account that: “The motion speed of particles during thermal motion depends on temperature, while the speed of motion of itinerant electrons in a metal has nothing to do with temperature, this is evident at least from the fact that thermal motion stops at a temperature of absolute zero, and the motion of itinerant electrons does not stop maybe.” [1]. And since the vibration frequency of the atom in this model will be related to the speed of the electron in the magnetic loop $v_p$, it becomes possible to assume that the process of wave energy transfer, at low temperatures (T° C) and absolute zero, is carried out in the volume of the loop with the longitudinal speed of the electron $v_p$.

For further consideration of the above contradictions, the following properties of the loop are proposed:
1. Energy of US wave propagates in the volume of the loop with the longitudinal velocity of the electron $v_p$.

2. Oscillation of the atom nucleus occurs under the action of the orbital centripetal force $F_{cent}$ of the electron rotating in the orbit of the atom every time the electron bends around the atom. This condition connects the natural frequency of vibration of the atom with the kinetic energy of the loop $E_k$.

In the molecular kinetic theory, the pressure in gas is defined as the process of collision of molecules on identical parts of the surface that limit the volume of gas for the same period of time [21]. This mechanism for determining the pressure for the volume of the loop is not acceptable due to the absence of chaotic motion of electrons in the loop according to the model shown in figure 3. Therefore, the internal pressure in the magnetic loop $P_p$ must be determined based on the centripetal force acting on the loop area, as in figure 5, based on the equation

$$P_p = \frac{F_{cent}}{S_p} = \frac{m_e \cdot \omega^2}{r_p \cdot S_p} = \rho_s \cdot a_{cent}^p$$

where $S_p$ - loop area, $m_e$ - electron mass, $r_p$ - loop radius, $\omega$ - circumferential speed of an electron, $\rho_s$ - surface density, $a_{cent}^p$ - centripetal acceleration.

![Figure 5. Rotation of an electron around the center of the loop point O.](image)

We can assume, that the process of adiabatic expansion of the loop volume $V_p$ as an increase in volume under elastic displacement of atoms from the equilibrium position by a certain distance $\Delta x$ as in figure 6 under the action of an external force $F_{ext}$.

![Figure 6. Adiabatic increase in the loop volume under the action of external force.](image)
The new loop volume $V_p^l$ under adiabatic expansion can be expressed from the condition of conservation of the radius of rotation of the electron in the loop $r_p$ - Const:

$$V_p^l = V_p + 2*\Delta V = S_p * (l_p^0 + 2*\Delta x) = \pi * r_p^2 * (2*a_i + 2*\pi*R_{orb}) =$$

$$= 2*\pi * r_p^2 *(a_o + \Delta x + \pi*R_{orb}) = S_p * l_p^1$$

Taking into account that the energy in the loop volume does not change $E_p = Const$ during the adiabatic process, we can write the following expression

$$E_p = P_p * V_p^l = \frac{n_e * m_e * \nu_{\omega} * \nu_{p}}{2}$$

Considering that the length of the middle line of the loop $l_p$ can be represented in terms of the longitudinal velocity of the electron as

$$l_p = \nu_p * \tau$$

then the pressure in the loop can be written by the following equation

$$P_p = \frac{E_p}{V_p^l} = \frac{n_e * m_e * \nu_{\omega} * \nu_{p}}{V_p^l} = \frac{n_e * m_e * \nu_{\omega} * \nu_{p}}{S_p * l_p^1 * 2} = \frac{n_e * \rho_p * \nu_{\omega} * \nu_{p}}{\nu_p * \tau * 2} = \frac{n_e * (\rho_p * \nu_{\omega})}{2}$$

Taking into account that the condition of loop continuity is actually indicated in brackets in equation (14), i.e., condition of constant areal density over time

$$\frac{\rho_p}{\tau} = Const$$

the equation (14) is transformed to the final form

$$P_p = \nu_{\omega} * Const * \frac{n_e}{2}$$

From equation (16) it follows that the internal pressure in the loop depends on the number of electrons $n_e$ in the volume of the loop $V_p$ and on the circumferential speed of electron rotation $\nu_{\omega}$ in the volume of the loop. The adiabatic increase in the volume of the loop upon displacement of atoms in the area of elastic deformation, as in figure 6, leads to a decrease in the pressure in the loop, which can only occur due to a decrease in the circumferential velocity of electron rotation $\nu_{\omega}$ (the number of electrons $n_e$ in the volume of the loop $n_e$ does not change since the adiabatic process occurs in a short time interval). Taking into account the condition of conservation of energy as the kinetic motion of the electron (12), in the volume of the loop, it turns out that a change in the circumferential speed of rotation $\nu_{\omega}$ leads to a change in the longitudinal speed of motion of the electron $\nu_p$ in accordance with the graph in figure 7.
Figure 7. The graph of the dependence of the change in speeds from the condition $E_k = Const$.

Thus, a decrease (increase) in the value of the circumferential speed of rotation of the electron $\nu_\omega^i$ leads to an increase (decrease) in the longitudinal speed of movement of the electron $\nu_p^i$. With the adiabatic expansion of the loop ($n_e = Const$), the pressure in the volume of the loop decreases and the longitudinal velocity of the electron increases, with a general decrease in the loop temperature, which will be expressed in an increase in the US velocity in the material. When the loop is compressed adiabatically, the pressure in the loop volume will increase due to the increase in the circumferential velocity $\nu_\omega^i$, the electron longitudinal velocity $\nu_p^i$ will decrease, with a general increase in the loop volume temperature, which will lead to a decrease in the US velocity in the material. In accordance with the adopted characteristics of the loop, with a change in the longitudinal velocity of the electron $\nu_p$, the vibration frequency of the atom $V_{at}$ will also change in accordance with the equation

$$V_{at} = n_e \frac{\nu_p}{2 \pi \nu_{orb}}$$

The equation (17) takes into account the number of electrons $n_e$ in the loop volume, since the displacement of the atom from the equilibrium position (oscillation) occurs from each electron located in the volume of the interatomic bond – the volume of the “magnetic” loop.

Thus, in accordance with the equation (17), an increase in the longitudinal velocity $\nu_p$ of an electron in a magnetic loop under elastic tension of the volume of a CL primitive cell should lead to an increase in the natural vibration frequency of the atom, which was noted in [8]. Accordingly, in the adiabatic process of elastic compression, the natural vibration frequency of the atom will decrease when the material is heated. It should be noted that the radius of the orbit of rotation of the electron around the atom does not change $R_{orb} = Const$ under both elastic tension and elastic compression of the material. Due to the fact that the loops are selected volumes in the space of the CL atomic plane, as in figure 8, it becomes possible to explain the experiments of A. Nadai by simultaneously receiving both heating and cooling in the same volume of a deformed rod by bending in the elastic area.
To do this, we use the Bernoulli hypothesis, the sections are flat before and after deformation, they only rotate about a certain line, which is called the neutral axis of the beam, while the fibers of the beam lying on one side of the neutral axis will stretch and, on the other, contract. If by “fibers” we mean a set of sequentially located on one straight line “magnetic” loops, then with elastic bending of the beam, the atomic plane in the material undergoes bending, where the interatomic distance parameter \((a + \Delta x)\) will increase along the X axis, and the parameter \((a - \Delta y)\) will decrease along the Y axis. In accordance with these changes along the X and Y axes, the volumes of the loops also change, which will lead to a change in the internal pressure and temperature in them. That is, an increase (stretching) of the interatomic distance along the X axis will lead to cooling of the loops along the entire axis, while a decrease (compression) along the Y axis will lead to heating of all loops. Thus, in the volume of the entire rod, the existence of two adiabatic processes at the same time is possible, which was observed experimentally by A. Nadai [12].

In fact, based on the change in the volume of the loop, which represents the volume of the interatomic bond of “collectivized” electrons, it was possible to explain the contradictions between the temperature drop and the increase in the velocity of ultrasonic waves transmitted in the volume of the loop in metals under elastic tension, and also to explain why two adiabatic processes (stretching and compression of the loop) which create a temperature gradient in the directions in the volume of the material. Based on the condition for the existence of these loops in the material, for any types of external influence, we will consider the process of changing the US velocity when heated.

It should be noted again that a contradiction during heating is a decrease in the US velocity in the material with an increase in the parameter of the interatomic distance \(a\) of the crystal lattice with a simultaneous increase in the natural frequency of vibration of atoms \(v_a\). We suppose that in the process of heating the material, the concentration of electrons \(N\) in the volume of the magnetic loop increases (that is, the parameter \(n_e\) in equation (12) increases). Then, proceeding from the fact that the process of interaction between the kinetic units (KU) of the material structure [22, 23] has the same electromagnetic nature, characterized by a constant value of their interaction [22], it can be assumed that in the process of heating the metal, the energy of the loop should not change, that is, \(E_p = \text{Const}\) and then it becomes possible to explain the above contradiction. Figure 9 shows a graph of the dependence of the product of velocities \(v_p \cdot v_p\) in the loop on the change in the product of the number \(n_e\) of electron masses \(m_e\) in the volume of the loop.

![Figure 8. Location of loops in the atomic plane.](image-url)
Figure 9. Graph of changes in the product of the circumferential $\omega_v$ and longitudinal $\omega_p$ velocities of an electron from the change in the number of masses of electrons in the loop volume.

It follows from this graph that with an increase in the number of electrons in the loop volume $V_p$, there is a simultaneous decrease in both the circumferential $\omega_v$ and longitudinal $\omega_p$ velocity of movement of each electron.

Due to the fact that the increase in the number of electrons in the loop was assumed to be temperature dependent, we will draw up a general graph of the dependence of the loop parameters on temperature, as in figure 10, where the initial conditions correspond to $20^\circ$ C.

Figure 10. General dependence of loop parameters on temperature.

An increase in temperature ($+T$) in the graph in figure 10 corresponds to an increase in the number of electrons ($n_e^0 + \kappa^e$) in the volume of the loop, which leads to a decrease in the longitudinal velocity of electrons $\omega_p$ and, accordingly, to a decrease of the US velocity in the material. In this case, the natural frequency of vibration of the atom under the action of electrons, in accordance with formula (17), will increase. So, for example, under the condition of doubling of electrons in the volume of the loop $V_p$, that is $(n_e^0 + \kappa^e) = 2 \times n_e^0$, it is possible to estimate the change in the electron velocities in the loop.
Thus, the decrease in velocities occurs in the same number of times, as a result of which the natural frequency of vibration of atoms can be found from equation (14) as

$$\nu_{at}^{i} = \left(\nu_{e}^{0} + \kappa\right) \cdot \frac{\nu_{p}^{i}}{2 \pi R_{orb}} = 2 \pi \nu_{e}^{0} \cdot \frac{\nu_{p}^{0} / \sqrt{2}}{2 \pi R_{orb}} = \frac{2 \pi \nu_{p}^{0}}{\sqrt{2}} \cdot R_{orb} = \sqrt{2} \nu_{at}^{0}$$

From equation (17) it follows that despite the decrease in the longitudinal velocity of the electron motion $\nu_{p}$, the natural frequency of vibration of the atom (s) in the bulk of the material increases. If the cooling of the metal (iron) is considered, as well as the process of decreasing the number of electrons in the volume of the loop, for example, at $(n_{e}^{0} - \kappa) = \frac{1}{2} n_{e}^{0}$ the velocities of electrons in the loop will increase

$$\left(\nu_{p}^{0} - \frac{n_{e}^{0}}{2} \right) \cdot m_{e}^{0} \cdot \nu_{p}^{0} = \frac{n_{e}^{0} \cdot m_{e}^{0} \cdot \nu_{p}^{0} \cdot \nu_{p}^{0}}{2}$$

and the natural frequency of vibration of atoms will decrease

$$\nu_{at}^{i} = \left(\nu_{e}^{0} - \frac{n_{e}^{0}}{2} \right) \cdot \frac{\nu_{p}^{i}}{2 \pi R_{orb}} = \frac{n_{e}^{0} \cdot \nu_{p}^{0} / \sqrt{2}}{2 \pi R_{orb}} = \frac{\sqrt{2} \nu_{at}^{0}}{\sqrt{2} \cdot \nu_{at}^{0}}$$

Thus, from a theoretical point of view, when the metal is cooled, the longitudinal velocity of the electron in the loop should increase, which, accordingly, entails an increase in the US velocity in the metal, with a decrease in the natural frequency of vibrations of atoms in the entire volume of the cooled metal. This theoretical conclusion coincides with the experimental work [24] in which the authors indicate: “... with decreasing temperature, there is an increase in hardness, a decrease in toughness and an increase in the propagation velocity of a longitudinal wave.”

4. Conclusions

Theoretical analysis of the change in the US velocity at heating iron and changing the US velocity in the area of elastic deformation of an iron rod, revealed that with identical changes in the parameters of a CL primitive cell - an increase in the crystal lattice parameter $a$ (interatomic distance in atomic planes), an increase in the natural vibration frequency of the atom $\nu_{at}$, an increase in the internal energy in the volume of material (the sound speed decreases with heating, and increases with elastic deformation). It is not possible to explain these diametrically opposite results of changes in the speed of sound, obtained experimentally, on the basis of the process of sound transmission by “electron gas”, or on the basis of the sound transmission through the interaction of atomic shells. Thus, the principle of “adiabatic approximation”, eliminating the mechanism of interatomic interaction, is not able to explain the physical processes of energy transfer of a sound wave and its changes under various influences on the material - heating and elastic deformation. As a consequence, it is necessary to consider the process of transfer of sound energy on the basis of a single process of interatomic interaction – the rotation of valence electrons around atoms. Valence electrons form a “collectivized” volume due to which there is
a contraction of atoms (positive ions) in the crystal lattice – a “magnetic” loop. The transfer of the energy of the sound wave is carried out in the volume of the “magnetic” loop due to the vortex motion of electrons, which was proposed by Maxwell. “... Faraday, who introduced the concept of magnetic lines into science, did not make any assumptions about their structure. The idea that in magnetic lines we are dealing with some rotational motion was developed by Maxwell. There is reason to believe that in magnetic lines we encounter the kind of rotational motion that is very common in nature. This is the so-called vortex motion.” [25].

The new mathematical model characterizes the process of changing the sound speed both during cooling of the metal and during heating, and also corresponds to adiabatic processes occurring in the area of elastic deformation of the rod. Thus, the model of the “magnetic” loop has established the physical processes occurring in the volume of “collectivized” valence electrons allocated in the space of the crystal lattice, on which the change in the speed of ultrasound in iron depends both during heating and cooling, and during elastic deformation. The general equation for the change in the speed of sound, which characterizes both processes – heating (cooling) and elastic deformation in iron will be a function of the change in the longitudinal speed of the electron \( \nu_p \) in the volume of the “magnetic” loop:

\[
\nu_j = \nu_p f(V_p, T_p)
\]

where this speed of electron motion \( \nu_p \) depends on the temperature of the entire sample and on the volume of the loop. The volume of the “magnetic” loop \( V_p \), in turn, depends on the external force \( F_{\text{def}} \) applied to the deformation of the sample. Additionally, it should be noted that in the course of theoretical analysis it was found that the energy of the “magnetic” loop does not change both in the process of elastic deformation and in temperature changes occurring with the volume of the material:

\[
E_p = \text{Const}
\]

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