The use of the rotating electromagnetic field for hardening treatment of details

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Abstract. The article discusses energy aspects of details’ hardening with convective flows of freely moving indenters under the conditions of the rotating electromagnetic field. Results of theoretical studies of the kinetics of the movement of the ferromagnetic indenters are presented and the energy model of the state of the rotating magnetic liquefied layer is proposed, formed under the influence of the rotating electromagnetic field.

1. Introduction
Despite the variety of methods to increase details durability, the issue of strengthening treatment of long parts with a relatively small cross-sectional area and inner surfaces of the hollow thin-walled parts is still incompletely resolved. To resolve this problem, the magneto-dynamic method is seen as promising, which in its physical-technological essence and the nature of the shock-pulse impact on the surface is a kind of dynamic methods meant to increase the strength of details with the convective flows of freely moving indenters. The most famous representatives of this group of methods are: vibro-impact [1], pneumodynamic and centrifugal rotary processes [2].

In [3, 4], it is shown that if non-equiaxed ferromagnetic particles are placed in a rotating electromagnetic field of sufficient strength, they come in a complex, chaotic movement, creating a kind of the rotating magnetic liquefied (RML) layer. For creation and practical use of the RML layer of ferromagnetic freely moving particles, the last are loaded into the device, creating a rotating electromagnetic field (REMF). The basis for these devices (Figure 1) is inductor 2, placed in housing 1. The inductor is a modified stator of an asynchronous motor. Cylindrical tube 3 of a non-magnetic material is installed into a stator boring, the inner surface of which limits the working area of the device. Tube 3 serves as the working environment that is made of the ferromagnetic material. Devices can be made with the water and air cooling.
Creation of the RML layer in devices under the influence of the rotating electromagnetic field, allows one to intensify a number of technological processes due to the complex flow of the physico-chemical effects in the working area such as stirring and dispersion, acoustic and electromagnetic phenomena, friction, high local pressures, electrolysis and shock-pulse interactions. Due to their relatively simple design, devices with REMF have been widely applied in technological processes of waste processing for electroplating, petroleum refineries, processing of animal waste, in powder metallurgy, oil refining, production of paints and polymers, in construction, and so on.

In this connection, the use of the rotating electromagnetic field is not without interest to improve the efficiency of technological processes of manufacturing parts [5]. Based on preliminary experimental studies, we have established that the chaotic motion of particles in the rotating electromagnetic field leads to a large number of collisions between particles, particles with the treated products, accompanied by both direct and glancing blows. The number of such collisions reaches $10^3 – 10^4$ by every particle per second. As the result of impact-impulse collision, there is a local elastic-plastic deformation of the surface of the parts in the working area of the device. Thus, we can conclude: devices with REMF can be quite successfully used to harden the surface layer of parts. To justify the technological possibilities of machining under conditions of REMF, we will analyze the main patterns of the dynamics of the RML layer.

2. The kinetic state of ferromagnetic indentors in the rotating magnetic liquefied layer

If bodies are placed in the electromagnetic field, then forces applied to the electric charges of these bodies will act on them. Thus, the ferromagnetic non-equiaxed indentors, becoming magnetized to saturation, can be considered as the elementary magnetic dipoles.

Let us define the kinematic characteristics of the magnetic indenter with mass $m$ and magnetic moment $p_m$, moving in a magnetic field formed by the superposition of a homogeneous constant field, and an inhomogeneous alternating field.

The value of the moment of couple of forces tending to turn the magnetic indenter in the direction of an external alternating electromagnetic field can be expressed as follows:

$$M_r = p_m B \sin \phi$$

(1)

where $\omega$ is the angular velocity of REMF;
$p_m$ is the magnetic moment of the ferromagnetic indenter;
$B = B_c + B_e \cos \omega t$ - REMF induction;
$\phi$ – the angle between the vector of the magnetic moment of the indenter and the vector of electromagnetic induction.

In addition, in an inhomogeneous field, the biasing (transportation) force acts on the magnetic indenter:

$$F_p = \chi UB \frac{dB}{dy}$$

(2)

where $\chi$ – magnetic susceptibility of the indenter material; $U$ – the volume of the indenter; $U = \pi d^2 l / 4$, where $d$ and $l$ – the diameter and the length of the indenter, accordingly; $\frac{dB}{dy}$ – the field gradient.
Under the action of the rotating moment, the ferromagnetic indenter rotates in a magnetic field with absolute angular speed \( \psi_a \), that in the fixed coordinate system is equal to the sum of the relative and transportation speeds, i.e.: 

\[
\psi_a = \psi_r + \psi_t .
\]  

(3)

On the basis of numerous experimental studies in [6], it is shown that with a high degree of correlation, the transportation speed of rotation of the magnetic particle is almost equal to the speed of rotation of the external magnetic field. This allows one to record \( \psi_t = \omega \).

To calculate the relative angular speed of ferromagnetic indentors in the electromagnetic rotating field, the following formula is received:

\[
\psi_r = \frac{\phi_1}{I} = \frac{d^2lB}{\mu_0K_{\mu}} \sin\phi_0 \sin\omega t ,
\]  

(4)

Where \( K_{\mu} = \mu \left( \frac{1}{\lambda} \right) \left( \frac{\lambda}{\lambda^2 - 1} \right) \); \( \lambda = l/d \) – the ratio of the length of the cylinder to its diameter.

Based on (9) and (10), and considering the fact that ferromagnetic indentors are magnetized to full saturation, the equation of the absolute rotation speed of the ferromagnetic indentors in the RML layer will take the form:

\[
\psi_a = \omega + \frac{d^2lB}{\mu_0K_{\mu}} \sin\phi_0 \sin\omega t .
\]  

(5)

From this equation it follows that the non-equiaxed ferromagnetic indenter in a rotating electromagnetic field at a constant angular speed moves with a variable angular speed, fluctuating relative to the induction vector of the magnetic field with a frequency depending on the magnitude of the moment of inertia of the indenter, its magnetic moment, the induction of the external magnetic field and the angle between the vector of the magnetic moment of the indenter and the magnetic field induction vector. To take into account all conditioning factors for the movement of indentors in the RML layer and to get admissible estimated analytical dependences is a very complex task from a mathematical point of view. So we will use the most versatile energy approach to the description of these processes and to the energy state estimate of ferromagnetic indentation in the RML layer.

3. The energy balance of the ferromagnetic indenter of the rotating magnetic liquefied layer

The proposed model is based on the following provisions:

- in a steady state of developed magnetic liquefaction, the energy roll-in to indentors from the external field is compensated by energy dissipation due to indentors interaction with the processed environment and as a result of inelastic collisions [4,7];
- changing the orientation of the indentors magnetic moments during the time between successive collisions is relatively small, which makes it possible to linearize the equation of motion of a ferromagnetic indenter in an external field;
- the energy roll-in from the field is provided through both progressive and rotational degrees of freedom;
- inter-indentor interactions lead to the establishment of an effective balance between progressive and rotational degrees of freedom of the balanced indentors;
- indenters of cylindrical shape have frozen-in magnetic moments.

To determine the energy imparted by the external alternating field with magnetic induction \( \vec{B} = B_0 + B_0 \cos \omega t \) to rotational degrees of freedom of indentors, possessing a magnetic moment constant by modulus \( p_m \), let us consider the equation of identity rotation relative to the axis perpendicular to the plane \( (\vec{B}, \vec{p}_m) \):
\[
\varphi_1 = \frac{P \sin \phi_0}{I_0} E(\omega t; 1) \approx \frac{P \sin \phi_0}{I_0} \sin \omega t.
\]

Let us assume the following equalities:
\[
\varphi' = \varphi_0' + \varphi_0'(t) - \varphi'_0 (t_0).
\]

The average amount of energy, transmitted by the external field to rotational degrees of freedom to one indenter during time \(T = \frac{\pi}{\omega}\), will be after averaging \(\frac{1}{2} I(\varphi'^2 - \varphi'^2_0)\) with respect to initial values \(\varphi_0\) and \(t_0\). Value \(T = \frac{\pi}{2}\) is selected as the time between collisions in the assumption that the collisional processes are implemented at the extreme points of the trajectory of reciprocation.

After conversion, taking into account equality (7) and the following correlation \(\langle \sin^2 \varphi_0 \rangle = \langle \sin^2 \omega t_0 \rangle = \frac{1}{2}\), the energy transmitted by the external field to ferromagnetic indentors at a time \(T\) at the rotational-oscillative motion will be written in the following expression:
\[
E_p = \frac{N}{2\pi} \left( \frac{1}{2} I(\varphi'^2 - \varphi'^2_0) \right) = \frac{N}{2\pi} \left( \frac{2\sin^2 \omega t_0}{I_0} \right),
\]
where \(N\) is the numeric concentration of indentors in the RML layer.

Let us determine the energy imparted by an inhomogeneous external field with a gradient of induction \(\frac{\partial B}{\partial y}\) to translational degrees of freedom of indentors. Not taking into account the resistance to progressive-oscillative motion, we will write the equation of motion:
\[
m\ddot{y}_1 = m \dot{\varphi}_0 \sin \omega t \cos \omega t.
\]

We integrate the equation of motion after transformation energy, transmitted by the field to indentors per time unit during progressive-oscillative motion, which can be written as:
\[
E_n = \frac{N}{2\pi} \rho m \frac{2}{\omega} \left[ \frac{\partial B}{\partial y} \right]^2.
\]

The total energy transmitted by the external field to indentors per time unit is equal to
\[
E_p = \frac{N}{2\pi} \rho m \left( \frac{\partial B}{\partial y} \right)^2 \left[ \frac{1}{m} + \frac{1}{I} \right].
\]

Let us consider the energy dissipation of indentors due to the resistance to deformation of the treated medium in the process of impact-pulse interaction. To simplify the supposed resistance, we shall consider it as linear to relevant speeds that is true neglecting effects of attached mass. The equation for the energy, dissipated by the indenter in the rotating magnetic liquefied layer per time unit, can be represented as
\[
E_{dtm} = 6\epsilon N \left( \frac{\lambda}{m} + \frac{\sigma}{m} \right),
\]
where \(\epsilon\) is the average energy of one degree of freedom, and the average is taken over the distribution for the corresponding linear or angular speed; \(\lambda\) and \(\sigma\) are, respectively, the friction coefficients of progressive and rotational motion.

In general, \(\lambda\) and \(\sigma\) depend on internal friction \(\eta\) of the processed material, the size and the shape of indentors, the Reynolds number for progressive and rotational motion, and the volume concentration of indentors in the working area covered by the rotating electromagnetic field are measured by parameter \(P\). In [8,9], it is shown that for spherical particles of the \(r\) radius interacting with the continuous phase at Reynolds numbers less than or about one, coefficients \(\lambda\) and \(\sigma\) can be determined from ratios:
\[
\lambda = 6\pi \eta r f(P), \quad \sigma = 8\pi \eta r^3 f(P), \quad f(0) = 1,
\]
where \(f(P)\) is the function that takes into account the influence of the pressure of indentors movement on resistance experienced by them.

For cylindrical indenters having \(1/d > 1\), taking into account (13), we will write:
\[
\frac{\lambda}{m} + \frac{\sigma}{I} = \frac{9}{2} \frac{\eta f}{\rho c_e} + \frac{15}{2} \frac{\eta f}{\rho c_e} = \frac{39\eta f}{2\rho c_e},
\]

\(1/d \rightarrow 1\), taking into account (13), we will write:
\[
\frac{\lambda}{m} + \frac{\sigma}{I} = \frac{9}{2} \frac{\eta f}{\rho c_e} + \frac{15}{2} \frac{\eta f}{\rho c_e} = \frac{39\eta f}{2\rho c_e},
\]
where \( r_e \) is the equivalent radius of the indentor, (under the condition of equality of the masses of the cylinder and the sphere) equal to \( r_e = \frac{3}{16} d^2 l \).

From the obtained expression, we can see that the viscous dissipation of energy of the rotational motion is more than three times greater than the dissipation of the progressive motion.

To account the dissipation due to inelastic collisions, we need to solve the problem of a single collision of two freely rotating indentors taking into account the surface friction, plastic deformation and speed changes of indentors during their convergence due to the dipole interaction. For this, we will limit ourselves by a semi-empirical approach, introducing the effective coefficient of elastic collisions \( \gamma \), describing the conservation of kinetic energy of colliding indentors in a single act, but we will present an expression of the energy dissipation due to collisions per volume unit and time [10] unit in the form of

\[
E_{\text{di}} \approx 6(1-\gamma)\varepsilon N. \quad (14)
\]

Thus, the energy dissipation of indentors in the RML layer will be equal to

\[
E_{\text{d\text{tm}}} + E_{\text{di}} = 6\varepsilon N \left( 1 + \lambda \frac{1}{m} + \sigma \frac{1}{m} \gamma \right). \quad (15)
\]

For the sustainable process of magnetic liquefaction of the rotating layer, the dissipation and conducted energy should be equal. Therefore:

\[
\frac{Np_m^2}{2\pi \omega} \left[ B_c^2 + \frac{1}{m} \left( \frac{\partial B}{\partial y} \right)^2 \right] = 6\varepsilon N \left( 1 + \lambda \frac{1}{m} + \sigma \frac{1}{m} \gamma \right). \quad (16)
\]

The equality (16) is valid under the assumption of the dominance of the viscous mechanism of dissipation and for this case allows determining the threshold value of the field induction gradient providing a stable mode of magnetic liquefaction of the rotating layer:

\[
\left( \frac{\partial B}{\partial y} \right)^2 = \frac{12\varepsilon N \omega m}{p_m^2} \left( 1 + \lambda \frac{1}{m} + \sigma \frac{1}{m} \gamma \right) - \frac{m}{1} B_c^2. \quad (17)
\]

As follows from (17), the sustainable magnetic liquefaction of the rotating layer depends on the induction of the rotating electromagnetic field, the magnetic moment of the indentor, its mass and moment of inertia, the frequency of the alternating magnetic field and the resistance coefficients to progressive and rotational motions.

### 4. Assessment of the energy state of the rotating magnetic liquefied layer at phase transitions

The ferromagnetic indentor of the RML layer has a reserve of kinetic energy, defined by expression (16), as well as potential energy related to the presence of a constant component of induction \( B_c \) of the external field. Thus, the total energy per unit of volume of the RML layer per time unit can be written in the form of

\[
E_{\text{te}} = \frac{Np_m}{2\pi \omega} \left[ \frac{p_m}{1} B_c^2 + \frac{p_m}{1} \left( \frac{\partial B}{\partial y} \right)^2 \right] - \frac{\omega^2}{1} B_c^2 \cos^2 \alpha - \frac{\omega^2}{1} B_c \cos \alpha, \quad (18)
\]

where \( \alpha \) – the average value of the angle between \( p_m \) and \( B_c \) for the period.

According to [11], the transition of the RML layer from the magnetic liquefied state in the “solid” phase will occur under the condition that ferromagnetic indentors stop the reciprocating motion. This process is realized when increasing the constant field induction to values satisfying the following relation:

\[
\frac{Np_m}{2\pi \omega} B_c \cos \alpha \geq \left( \frac{\partial B}{\partial y} \right)^2. \quad (19)
\]

From the last inequality, we can obtain the expression for the induction of the constant field corresponding to the transition disorder – order:

\[
B_c \geq \frac{p_m}{2\pi \omega^2} \left( \frac{\partial B}{\partial y} \right)^2. \quad (20)
\]

In inequality (20), the \( \cos \alpha = 1 \) is adopted that can be justified by the assumption about the collinear orientation of vectors \( p_m \) and \( B_c \) in the ferromagnetic indentor transition from the magnetic liquefied state to the “solid” phase.
The induction of the constant field can be defined, at which the mechanical motion of indentors in the structure of the "solid" phase stops, wherefore the energy of the rotational motion of the indenter will be equated to the energy of inter-indentors interaction. In the approximation of the nearest neighbors and collinear orientation of magnetic dipoles, let us write:

\[ \frac{1}{2} \rho_m B_v^2 = \frac{\mu_0}{4\pi} \frac{\rho_m^2}{r_e^3} + p_m B_c ; \]

and for the required value of the induction, we will receive:

\[ B_c = \frac{1}{2} \rho_m B_v^2 - \frac{\mu_0 \rho_m}{4\pi r_e^3} . \]

5. Conclusion

1. The proposed magneto-dynamic method of treatment based on creating a convective flow of ferromagnetic indentors under the conditions of the rotating electromagnetic field rightly expands the theological possibilities of dynamic methods to increase the strength of details and has its own specific technological purpose associated with its use in operations to increase the strength details with expressed paramagnetic properties. These parts include thin-walled tubes, stringers, belts, spars, that are widely used for aircraft manufacturing.

2. From the obtained results of theoretical studies, it follows that the kinematic characteristics of the ferromagnetic indentors are determined by the parameters of the field – induction of constant and alternating fields, frequency and the gradient of induction of the alternating field, and magnetic and inertial characteristics of indentors.

3. The optimum ratio between the magnetic field parameters and inertial and magnetic characteristics of indentors proposed based on the energy model of the RML layer, allows one: to justify the energy potential of ferromagnetic indentors, giving the effect of elastic-plastic deformation of the treated medium, leading to its strengthening; to define the threshold value of the magnetic field gradient providing a stable mode of magnetic liquefaction of the rotating layer; to justify the induction of the constant field in which the mechanical movement of indentors in the structure of the “solid” phase stops.

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