DEMAGNETIZATION OF FINE FERROMAGNETIC MATERIALS

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Abstract

Analysis of the works on the magnetic separation of minerals in the preparation of ores shows that this process has proven to be successful in the extraction of valuable minerals from waste. As for the enriched product, the primary separation (with the initial content of the valuable mineral α <50%) gives a significant quality increase. Since the liberated valuable mineral is not removed from further processing, the initial content of the valuable mineral keeps increasing through the stages. On the other hand, due to flocculation, the capture of the non-metallic phase also increases. The probability of capture is proportional to the product of valuable (P_M) and non-valuable ($1-P_M$) minerals content. Hereafter, without the use of special methods, it is not possible to extract these particles from the mass of the concentrate, since the probability of the removal of liberated non-metallic particles asymptotically tends to zero. Thus, it is theoretically impossible to obtain pure magnetite concentrates by magnetic methods that are currently used at iron ore preparation plants.

Production of pure concentrates requires reducing of all particles to zero residual magnetization, i.e. they need to be demagnetized before further non-magnetic separation.

The problems of demagnetization of fine ferromagnetic particles have been studied as long as their magnetic separation [6]. At the moment, in the preparation processes demagnetizing devices with an alternating magnetic field of an industrial frequency of 50 Hz are used [7]. In an alternating field of such a frequency, the floccules of magnetic particles in the form of strands rotate, which reduces their

dimensions. The effect of such a field is judged on the improvement of the selectivity indices compared to control samples that were not subjected to an impact. The measurement of sizes of particle aggregates, or floccules, is carried out either via photo recording or is assessed visually in a transparent bath of a separator with a water flow and a sufficiently small number of particles, which allows observing directly the behavior of these aggregates.

The main condition for the demagnetization of a ferromagnetic body is the stabilization of its position in space with regard to the changing vector of the external magnetic field [9]. It is not possible to fix the position of all individual particles in suspension by some mechanical method. The material body, no matter how small it is, has a mechanical inertia. Mechanical inertia is proportional to the mass of the particle; it is considerably larger than the magnetic one and shows itself already at frequencies of an external alternating magnetic field of several dozens of thousands of Hz.

Thus, if the vector of the external magnetic field outstrips the position of the axis of easy magnetization of the particle, the prerequisites for its partial demagnetization are developed. Moreover, if such an advance is more than 90°, then demagnetization can be carried out to the full.

The purpose of the paper is to study the process of demagnetization of ferromagnetic particles in the suspension flow.

Scientific novelty is in the fact that the dependence of the lag angle of the turn of magnetic particles in the aqueous medium on the angle of the external magnetic field vector is found. This makes it possible to determine the conditions for achieving the demagnetization effect of ferromagnetic particles in the suspension flow.

Research methodology: numerical mathematical modeling and recording of the results of experimental studies by microscopic observations.

Inertia of a mineral particle in an aqueous medium. Suppose that a particle of a spherical shape moves along with the flow of suspension and instantly falls within a magnetic field superimposed on the flow. It starts moving toward the highest gradient. According to Newton's law, (forces are normalized to specific, related to the mass of the particle):

$$\frac{dU_P}{dt} = F_M - F_g - F_\mu, \left[\frac{m}{s^2}\right];$$

where the force of the magnetic action on a particle in an isodynamic field is:

$$F_M = \mu_0 \cdot \chi_P \cdot H_0^2 \cdot c;$$

the force of viscosity of medium:

$$F_\mu = \frac{18 \cdot \mu \cdot U_P}{\delta_P \cdot d_P^2};$$

the force of gravity:

$$F_g = g \cdot \frac{\delta_P - \delta_W}{\delta_P}.$$

Under the action of these forces, the particle moves relatively to the medium and experiences an additional damping action of the viscosity of the medium.

One of the constituent forces depends on the velocity of the particle, the rest are constants; therefore, the equation of the law of a particle motion can be written as follows:

$$\frac{dU_P}{dt} = -\frac{18 \cdot \mu}{\delta_P \cdot d_P^2} \cdot U_P + \left(\mu_0 \cdot \chi_P \cdot H_0^2 \cdot c\right) - g \cdot \left(\frac{\delta_P - \delta_W}{\delta_P}\right),$$

where: μ – coefficient of dynamic viscosity of water, [N·s/m^2]; $\mu_0 = 1.26 \times 10^{-6}$ – absolute magnetic constant, [N/A^2]; d_P – particle size, [m]; δ_P, δ_W – particle and water densities, [kg/m^3]; χ_P – specific magnetic susceptibility of a particle, [kg^{-1}]; c – external magnetic field variation factor, [m^{-1}]; H – magnetic field intensity, [A/m].

The solution of this equation is trivial; it shows that the time of the transient process of particle motion is 0.006 s.

The steady-state particle velocity is about 0.097 m/s. During this period, the particle passes a distance equal to its diameter. On this basis, we can conclude that particles in an aqueous medium in case of slowly changing conditions react instantly to a change in the ratio of the forces effecting on them; in terms of demagnetization, the

frequency of the change in the magnetic field should be greater than the value being reciprocal to the period of the transient process.

Methods and devices currently used to demagnetize ferromagnetic particles in a suspension. Historically, the first and most obvious way to study the behavior of ferromagnetic particles in a magnetic field is a visual one. To do this, transparent baths with the application of a magnetic field were created; a pure water flow, containing an insignificant amount of ferromagnetic particles of known physical parameters was supplied. Based on visual observations, the frequencies of rotation of the floccules were recorded as well as their length and thickness. To increase the objectivity of the measurement indicators, video and photo recording as well as scaling of the actual size of the floccules were applied. It was found that at a frequency of about 450 Hz magnetic particles moved in the form of a cloud. The static state of the individual particles was not detected.

Fig. 1 shows the results of measurements of the length of magnetic strands in an alternating magnetic field [5]. As follows from the graphs, the length of the floccules increases with the decrease in a particle size, since it is accompanied by their coercive force growth. An increase in the frequency of the magnetic field reduces the size of the strands. Destruction of strands to the size of individual particles was not obtained.

Paper [7] represents the results of studies of the alternating magnetic field effect on the flow of a ferromagnetic suspension, coming to the magnetic recovery of magnetite concentrate. The authors call the operation of an alternating magnetic field effect on the suspension flow as *demagnetization*. The effect of the impact was evaluated according to the results of improving the quality of the concentrate obtained both without its treatment with an alternating magnetic field, and with such a treatment. Naturally, with the influence of the alternating field, the selectivity indices are improved, since a partial destruction of the floccules occurs. Consequently, additional liberation of constrained released non-metallic particles, which are removed to a depleted product, takes place. The selectivity indices improve with an increase in the intensity and frequency of the magnetic field. Naturally, an increase in the amount of released fraction in the free state in the suspension

reduces the content of a valuable mineral in a depleted product. The greater the suspension density is, the more visible the effect of magnetic treatment by an alternating field is, since the capture of non-metallic particles is proportional to the solid content in the suspension. A significant increase in suspension density leads to a decrease in the mobility of particles in it; thus, starting with a content close to 50%, the effect of magnetic processing again decreases [7].
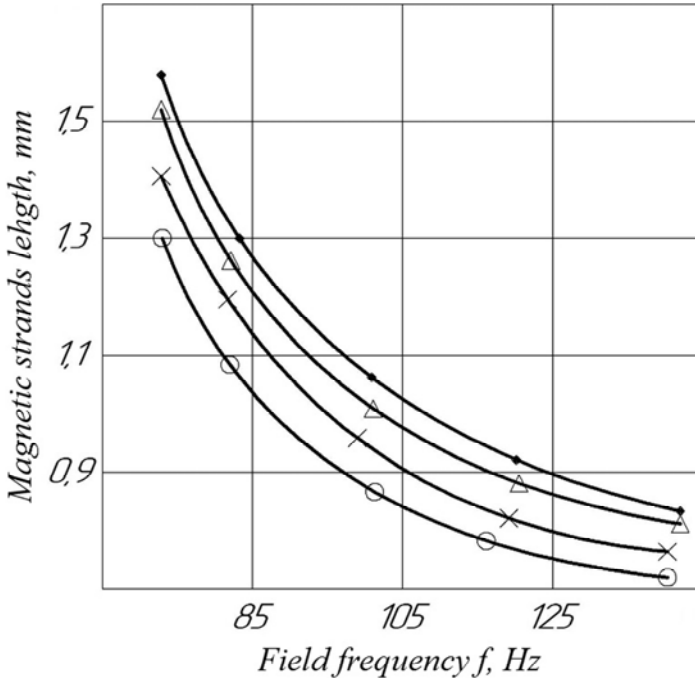

Fig. 1. Dependence of the *average length of magnetic strands* on the *frequency of the traveling magnetic field* during the dry separation of magnetite ore of various sizes on a top-feed drum separator: 1 – fraction –53 μm; 2 – fraction –74 μm; 3 – fraction –104 μm; 4 – fraction –147 μm.

Thus, experimental studies, known in the scientific literature, show the effectiveness of preliminary treatment of the suspension flow by an alternating magnetic field. However, there is no valid information about the demagnetization degree of ferromagnetic particles.

At present, demagnetization is carried out in devices that represent a non-magnetic pipeline through which a suspension flows and around which there are mounted electric coils with a reduction in the number of turns. As a result, the intensity of the magnetic field gradually decreases from the saturation intensity to zero. Thus, one demagnetization condition is fulfilled. Thus, the condition for the motionlessness of the particles is not met.

The design and practical use of the applied demagnetizing devices suggest that the demagnetization of particles of the heavy fraction can be carried out in an alternating magnetic field without much influence on the position of the particles. Thus, it is believed that, after leaving the demagnetizing apparatus, the particles of the heavy fraction are demagnetized.

Processing of a suspension by an alternating magnetic field before hydrocycloning [7] has demonstrated that the classification efficiency increases up to 20% with an increase in the demagnetization degree up to 90%. The recovery of iron ore concentrate with the application of an alternating magnetic field gives an increase in the iron content by about 1%.

The condition for the demagnetization of particles is that during the period of the change in the polarity of the magnetic field, the particle does not change significantly its position in relation to the magnetic field vector. It is possible to meet this condition in two cases:

– when the particle is mechanically rigidly fixed in space;

– when the particle does not have time to follow the change in the vector of the external demagnetizing magnetic field.

Consider how an instantaneous fixation of the position of a particle in space is possible.

The change in the intensity of the field, created by a multipolar magnetic system, can be described in the simplest way by functions of the form:

$$H_X = H_0 \cdot \exp(-c \cdot X) \cdot \cos(c \cdot Y);$$
$$H_Y = H_0 \cdot \exp(-c \cdot X) \cdot \sin(c \cdot Y);$$

where H_0 – field intensity on the surface of poles, [A/m]; $c = \pi / S_{POL}$ – magnetic field variation factor, [m^{-1}]; S_{POL} – polar

pitch, [m]; X – coordinate directed normally to the line of the vertices of the poles, [m]; Y – coordinate directed normally to the axes of the poles, [m].

Consider the case of an alternating magnetic field of a stationary magnetic system. Assume that the frequency of the field change is ω, while the length of the strand (floccule) on the drum surface is a. Then, under favorable conditions, the speed of the strand moving on the drum surface will be:

$$U_S = 2 \cdot \pi \cdot \omega \cdot a.$$

The gradient of the intensity along the axis Y from the expression for H_Y is:

$$\frac{dH_Y}{dY} = H_0 \cdot c \cdot \exp(-c \cdot X) \cdot \cos(c \cdot Y).$$

Magnetic force F_{M1} pulling the floccule to the pole is:

$$F_{M1} = \mu_0 \cdot \chi_F \cdot H_Y \cdot \frac{dH_Y}{dY},$$

where χ_F – <u>specific magnetic susceptibility</u> of floccule, [kg^{-1}].
Floccule is forced against a drum surface by a magnetic force:

$$F_{M2} = \mu_0 \cdot \chi_F \cdot H_X \cdot \frac{dH_X}{dX}.$$

The equilibrium of the floccule on the drum surface will rise under the condition:

$$F_{M1} = \frac{F_{M2}}{k_F},$$

where k_F – coefficient of friction.

In case of a multipolar system, the floccule, located between the poles, experiences the action of two oppositely directed horizontal forces:

$$F_{MY}^1 = \mu_0 \cdot \chi_F \cdot H_0^2 \cdot c \cdot \sin((S_{POL} - a) \cdot c);$$
$$F_{MY}^{11} = \mu_0 \cdot \chi_F \cdot H_0^2 \cdot c \cdot \sin((S_{POL} + a) \cdot c).$$

Vertical component is:

$$F_{MX} = \mu_0 \cdot \chi_F \cdot H_0^2 \cdot c \cdot \cos(a \cdot c).$$

The equilibrium condition for floccule is:

$$F_{MX} k_F = F_{MY}^1 - F_{MY}^{11}.$$

Solving the last equation for a, we obtain:

$$\sin \frac{\pi \cdot a}{S_{POL}} = \frac{k_F}{2} \cdot \cos \frac{\pi \cdot a}{S_{POL}},$$

whence:

$$a = \frac{S_{POL}}{\pi} \cdot \arccos k_F^{-0.5}.$$

According to experimental data [5], along with frequency increasing, strands begin to decrease; at a frequency of 400 Hz they become indistinguishable for the naked eye.

The analysis of the data in Fig. 1 makes it possible to draw following conclusions. Since the magnetic susceptibility decreases with reduction in size, the strands become shorter, therefore their speed declines. However, as the frequency increases, their velocities no longer depend on the size, since the resistance to movement of the floccule does not depend on an individual particle, but rather has an average value, which depends on the size and speed of the floccule. Determine at what frequency floccules and particles are broken away from the drum surface when the sign of the field strength changes.

Consider the effect of an alternating magnetic field on magnetic particles. The latter usually have an elongated shape, close to the ellipsoid of rotation with the ratio of the major axis to the small being $\Lambda = 2$. The particle is oriented by a long axis (axis of easy magnetization) along the external magnetic field vector. In the case of an alternating magnetic field, the particle follows the change in this vector. The magnetic force that orients the particle is [10]:

$$F_{M1} = \frac{1}{\delta \cdot d} \cdot \mu_0 \cdot H^2 \cdot (k_a - k_b) \cdot \sin \alpha,$$

where k_a, k_b – volumetric magnetic susceptibilities of the particle along the long and short axes, [m^{-3}]; α – angle between vector H and axis a of the particle.

The values of k_a, k_b depend on the magnetic susceptibility of the substance k_M and on the relation $a/b = \Lambda$, that is, from the demagnetizing factor N along each of the axes [9].

The force of the viscosity prevents the rotation of the particle. As the particle rotates, then $U = 2 \cdot \pi \cdot \omega \cdot a$, where ω is the frequency of external magnetic field change.

Equation of a particle motion is $F_{M1} = F_\mu$, since forces are specific. Taking into account that $\omega = \dfrac{d\alpha}{dt}$, we have:

$$\frac{36 \cdot \pi \cdot \mu \cdot d\alpha}{\delta \cdot d \cdot dt} = \frac{\mu_0 \cdot H^2 \cdot (k_a - k_b)}{\delta \cdot d} \cdot \sin\alpha.$$

Denoting $B = \mu_0 \cdot H^2 \cdot (k_a - k_b)$ and $36 \cdot \pi \cdot \mu = A$, we obtain the equation:

$$\frac{d\alpha}{\sin\alpha} = \frac{B}{A} dt.$$

The solution of this equation has the form:

$$\ln(\csc\alpha - ctg\alpha) = -\frac{B}{A} \cdot t + \ln C.$$

Select the initial conditions from such considerations. We assume that the field is changing instantly from $-H1$ to $+H1$. It is natural that a particle cannot follow the field immediately, hence $\alpha_0 = \pi/2$. Further, the field remains at the level $+H1$ and with $t \to \infty$ $\alpha \to 0$. So, $t = 0$, then:

$$\ln\left(\csc\frac{\pi}{2} - ctg\frac{\pi}{2}\right) = \ln C,$$

that is: $\csc\dfrac{\pi}{2} = 1$, $ctg\dfrac{\pi}{2} = 0$, then $\ln C = 0$, $C = 1$.

In this case, the final solution of the equation of motion takes the form:

$$\csc\alpha - ctg\alpha = \exp\left(-\frac{B}{A} \cdot t\right).$$

Simplifying the last expression, we obtain the function of the angle of lag from the frequency:

$$\alpha = 2 \cdot arctg \exp\left(-\frac{B}{2 \cdot \omega \cdot A}\right).$$

The magnitude of this angle varies depending on the variation frequency of the magnetic poles under the concentrated mass on the drum surface. At a frequency of 500 Hz, the angle of lag is already considerable and the particles make oscillatory motions, not having time to make a rotation. At a frequency of 1 kHz, the angle of lag is greater than 45°. Demagnetization will be observed in the case when the angle of lag is more than 90°. In this case, the opposite direction of the particle magnetization and the vector of the external magnetic field is observed. When the angle of lag reaches 180°, the conditions for demagnetizing the particles will be ideal.

Demagnetization of ferromagnetic particles in the flow of suspension. Demagnetization of the ferromagnetic sample is carried out as follows. The sample is fixed rigidly in space where a magnetic field will be induced. The orientation of the sample is such that the easy-magnetization axis is parallel to the external magnetic field vector.

The field strength corresponding to the saturation of the sample is established.

Multiple changes of the magnetic field intensity vector direction are made. As a result, the sample will have a residual magnetization, which is located on the curve of initial magnetization.

The amplitude of magnetic field intensity is decreased, and the procedure is repeated. This is done until the magnetic field intensity is reduced to zero. As a result, the sample will be completely demagnetized. The main condition for demagnetization is its rigid position in a variable magnetic field. When the sample is not fixed, it tends to change its position in accordance with the change in the direction of the external magnetic field vector, being oriented by the axis of easy magnetization along the vector of the external magnetic field. The speed of the sample following the rate of change of the external magnetic field depends on the magnetization intensity of the sample, on the environmental parameters, and on the conditions for

sample fixing in space. The magnetization of a non-fixed sample does not change.

In order to achieve reversal magnetization of particles in the suspension, where, as it is known, ferromagnetic particles can orientate freely along the vector of the external magnetic field, it must be altered with a rate that exceeds the rate of mechanical movement of the sample in this field. The angle of lag between the angle of particle rotation and the magnetic field vector should be more than 90°, for a particle to have time time to follow the magnetic field, which at that time has a unipolar direction. Determine what the frequency of the field change should be in this case.

Suppose that the suspension stream contains particles of ferrosilicon as the solid phase, which have the form of ellipsoids of rotation with a major axis a and a minor axis b. Assume also that the magnetic field is uniform.

Upon entering a magnetic field, each particle of such type is magnetized, and "magnetic masses" are formed at its ends. These masses, interacting with an external magnetic field, cause the rotation of a particle with respect to a minor axis, i.e. are oriented by a large axis along the external magnetic field vector. This leads to a change in the demagnetizing factor of the suspension region and, as a consequence, to a change in the magnetic susceptibility of this region. This is so-called magnetic structuring. Prior to entering the magnetic field, the particles are oriented by a long axis arbitrarily in space, and the distribution of the orientation angles is uniform. Moreover, after getting into the field, the orientation of all the particles is the same.

The moment of rotation effecting the particle is [8]:

$$M_{MECH} = f \cdot a \cdot \sin \alpha_1,$$

where $f = m \cdot H$ – force effecting the ends of a particle; α_1 – angle between the major axis of the particle and the external magnetic field vector; m – magnetic mass.

Considering that $m = \Phi$, i.e. the magnetic flux passing through the cross section of the particle S, we obtain $f = \Phi \cdot H$. It is also known that $\Phi = B \cdot H$ and $B = \mu_0 \cdot \overline{\mu} \cdot H$, where $\overline{\mu}$ –

magnetic permeability of a particle; $\mu_0 = 1.26 \times 10^{-6}$ – absolute magnetic constant; B – magnetic induction in the particle region. Then:

$$M_{MECH} = \mu_0 \cdot \overline{\mu} \cdot S \cdot H^2 \cdot a \cdot \sin \alpha_1 = K_1 \cdot \sin \alpha_1.$$

The rotation of particles is prevented by the moment due to the reaction forces, which depend on the viscosity of the medium. The viscosity of the medium is [5]:

$$F_\mu = \frac{18 \cdot \mu \cdot U_P \cdot m_P}{a^2 \cdot \delta_P},$$

where μ – coefficient of dynamic viscosity of the medium, [N·s/m^2]; U_P – linear speed of rotation of the ends of the particle, [m/s]; m_P – particle weight, [kg]; δ_P – particle density, [kg/m^3]. In such a manner:

$$M_\mu = F_\mu \cdot a.$$

The linear velocity of the ends of the particle is $U = a \cdot \dfrac{d\alpha_1}{dt}$. The general expression for the static reaction moment is:

$$M_\mu = \frac{18 \cdot \mu \cdot m_P}{a^2 \cdot \delta_P} \cdot \frac{d\alpha_1}{dt} = K \cdot \frac{d\alpha_1}{dt}.$$

The angle of rotation of the particle can be determined from equality:

$$M_\mu = M_{MECH} + J_1 \cdot \frac{d\omega}{dt},$$

where J_1 – moment of inertia of a particle.

With an error not exceeding 5%, assume that $\sin \alpha_1 = \alpha_1$. Then the equation of dynamic equilibrium of the particle takes the form:

$$J_1 \cdot \frac{d^2\alpha_1}{dt^2} - K \cdot \frac{d\alpha_1}{dt} + K_1 \cdot \alpha_1 = 0.$$

The roots of the characteristic equation of this differential equation are:

$$p_{1,2} = \frac{K \pm \sqrt{K^2 - 4 \cdot J_1 \cdot K_1}}{2 \cdot J_1},$$

and the solution has the form:

$$\alpha_1(t) = \alpha_0 \cdot \left(1 - \frac{p_1}{p_1 - p_2} \cdot \exp(-p_1 \cdot t) + \frac{p_2}{p_1 - p_2} \cdot \exp(-p_2 \cdot t)\right).$$

Estimate the numerically obtained solution for such initial data:

$$a = 10^{-3}\,[m]; \ \ \delta_P = 4000 \left[\frac{kg}{m^3}\right]; \ \ \overline{\mu} = 2;$$

$$H = 50000 \left[\frac{A}{m}\right]; \ \ \mu = 10^{-3} \left[\frac{N \cdot s}{m^2}\right].$$

The moment of inertia will be: $J_1 = 0.52 \times 10^{-12}$. Coefficients are: $K_1 = 5 \times 10^{-6}$, $K = 9.42 \times 10^{-9}$. The roots of the characteristic equation are equal to: $p_1 = 17.67 \times 10^3$, $p_2 = 0.59 \times 10^3$. Equation of rotation of a particle in numerical expression is:

$$\alpha_1(t) = \alpha_0 \left(1 - 1.03 \cdot \exp(-17.67 \cdot 10^3 \cdot t) + 0.03 \exp(-0.59 \cdot 10^3 \cdot t)\right).$$

Time can be expressed in terms of the velocity of the suspension flow in the area of action of the magnetic field. Alternatively, it is possible to set the condition that the angle of rotation of the particles should not be more than 5-10% of the initial value. Hence, we determine the time of action of a magnetic field of one polarity. To do that, confine ourselves to a member with the largest exponent and the largest coefficient, since the second term of the equation introduces a small fraction of the effect on the particle motion. Then:

$$\Delta t = \frac{\ln 0.95}{-17.67 \cdot 10^3} = 3 \times 10^{-6}\, s.$$

The frequency of the magnetic field will be:

$$f = \frac{1}{\Delta t} = 0.33 \times 10^6\, Hz = 330\ kHz.$$

The time of a field exposure with a frequency of 50 Hz corresponds to 0.01 s. As a result, the angle of lag of the particle orientation from the magnetic field vector is about 0.0003 of its initial position.

Thus, the effect on a ferromagnetic suspension by an alternating magnetic field with a frequency of 50 Hz cannot cause demagnetization of particles of a ferromagnetic material, since these particles have time to be oriented by the axis of easy magnetization along the external magnetic field vector. Hard fixing of the particle position in an alternating magnetic field is not observed. Some improvement in the rheological parameters of the ferromagnetic suspension, which passed through the demagnetizing device, can be explained by the mechanical destruction of floccules to the dimensions that will be determined by the value of the residual magnetization of the ferromagnetic particles.

The time of action of an alternating magnetic field of one polarity is equal to half a period: $t = (2 \cdot \omega)^{-1}$. On the basis of which obtain the function of the angle of lag from the frequency:

$$\alpha = 4 \cdot arctg \exp\left(-\frac{B}{A} \cdot \omega \right).$$

Thus, the weighting agent particles at frequencies up to 100 Hz practically succeed in following the vector of the external magnetic field with lag of 1°. Over 1000 Hz, the lag is considerable and amounts to more than 90°. The reversal magnetization of particles begins. At a frequency of 100 kHz, there are sufficient conditions for remagnetization of the particles, since the angle of lag is 177°.

Table 1

The angle of lag of the particle turn to the external alternating magnetic field vector

Frequency, kHz	0.01	0.05	0.1	0.5	1	3	5	10	50	100
Angle, deg.	0	0	1	72	120	160	168	172	176	177

The angle of lag can be used as a measure of the demagnetization of particles: $K_{DEM} = \sin(\alpha - 90)$, since demagnetization starts, when the component of the external magnetic field vector begins to have an opposite direction to the magnetization vector of the particle.

Even if we assume that the magnetic particles are completely demagnetized, then, falling into the Earth's magnetic field, they acquire the magnetization corresponding to this field, and unite into aggregates. Thus, it is not possible to demagnetize the weighting agent particles completely.

Demagnetization experiments. To obtain high-quality magnetite concentrate at preparation plants, multi-stage magnetic separation is used. Since the ferromagnetic minerals of magnetite are characterized by a residual induction of magnetization, the particles of magnetite ore spontaneously form floccules, inside which the waste particles are trapped, which reduces the quality of the concentrate. In addition, magnetic flocculation reduces the efficiency of classification, which increases the circulating load on the mills.

Classification of the crushed product in the second and third stages of grinding is carried out in hydrocyclones. Since the floccules of particles of predefined grain-size class have a larger size, they go to the underflow and return to the mill for grinding, which increases the circulating load and reduces the grinding rate. Therefore, it is advisable to demagnetize the suspension, entering the hydrocyclones.

A suspension of magnetite of *Poltava mining and concentration complex* with a content of grain-size class of less than 50 μm of more than 96% and a solid phase concentration of 100 g/l was used for the studies.

Preliminary magnetization was carried out in a constant magnetic field with an induction of 0.25 T. Demagnetization was performed in pulsed mode in a laboratory device [1]. Demagnetization consists in placing the particle in an external alternating magnetic field, the induction of which decreases smoothly from the maximum value, which should be greater than the residual magnetization of magnetite particles, to zero. Herewith, the demagnetization occurs according to the hysteresis curves. In the coil of the solenoid, damped current oscillations are created, and the number of oscillations must be greater than 5. This is ensured by the corresponding Q-factor of the

oscillatory circuit. In this case, all particles inside the solenoid are subjected to demagnetization in places where the maximum induction of the magnetic field is greater than the residual magnetization of the particle.

In general, we can assume that the residual magnetization of magnetite plays a negative role in the separation of minerals. Thus, its reduction, or demagnetization, is an actual task.

It is energetically and constructively expedient to perform demagnetization in a pulsed mode.

Theoretical and quantitative relationships obtained for the degree of demagnetization of magnetite particles were verified by microscopic examination of the suspension, which was processed by a high-frequency magnetic field. The measurement standard is shown in Fig. 2.

Fig. 2 and 3 demonstrate photographs of particles of the magnetite suspension with magnification x24, subjected to magnetization (Fig. 2), and having passed through a field of decreasing intensity with a frequency of 20 kHz (Fig. 3). It is qualitatively possible to say for sure that the particle size decreases significantly. Both suspensions underwent intensive mechanical mixing, and the particle size in them was not changed. Thus, the mechanical effect does not have a significant impact on the size of the floccules.

Fig. 4 shows a photograph of particles of the suspension with magnification x56, which were magnetized by a constant magnetic field with an induction of 0.25 T. The division value of the measuring rule corresponds to 10 μm. As it can be seen, the length of the floccule reaches 300 μm (0.3 mm).

Having subjected the same suspension to the action of an alternating magnetic field with a frequency of 20 kHz and a decreasing intensity, we obtained floccules of smaller size (Fig. 5) – about 100 μm (0.1 mm), while the structure of these aggregates, consisting of chains of individual particles, is clearly observed. It can be concluded that the magnetite particles have been partially degaussed, but complete demagnetization was not achieved.

Having subjected the same suspension to the action of an alternating magnetic field with a frequency of 70 kHz (Fig. 6), completely demagnetized particles, separated from one another, were

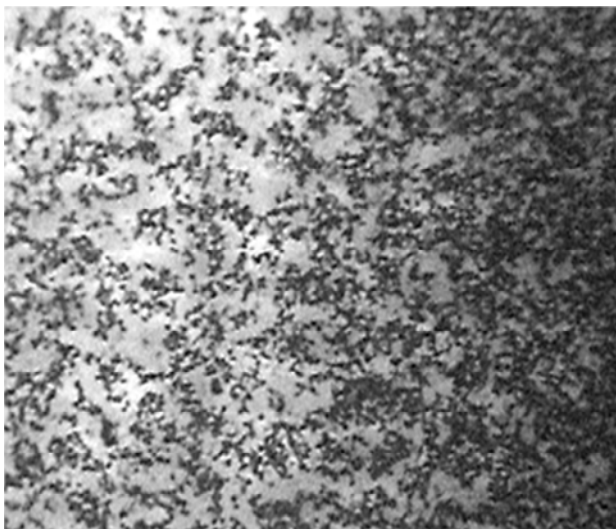obtained. It should be noted that the samples were screened from the Earth's magnetic field.

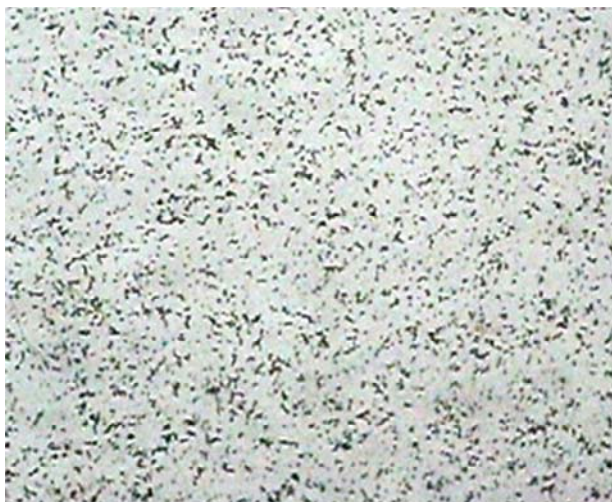**Fig. 2.** Suspension of magnetized magnetite particles

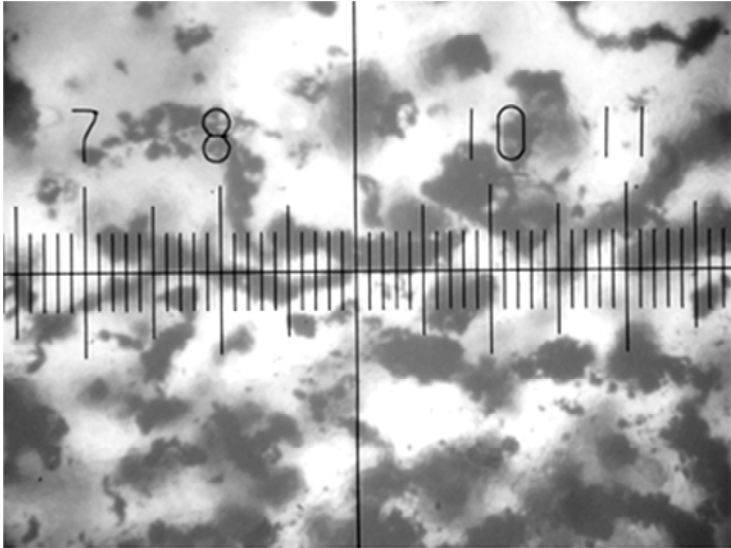**Fig. 3.** Suspension of demagnetized magnetite particles

Fig. 4. Magnetized suspension

The study of the particle sizes in Fig. 6 allows concluding that practically all particles have a size of less than 20 μm. When classifying such particles, for example in a hydrocyclone, they will all go into an overflow product, in contrast to the magnetized particles, a large part of which in the form of floccules will fall into the underflow and will return to the mill. Consequently, the use of complete demagnetization of magnetite particles prior to their classification will reduce the value of the circulating load on the mill, which will increase the efficiency of its operation. It is possible to separate particles of this size in sensitive devices. These may be hydrocyclones with a diameter of cylindrical part of 50 mm or less, glazed in the area of a working part.

In addition, magnetite minerals in particles of such a size are almost completely released, which theoretically makes it possible to obtain ultrahigh-quality concentrates.

When the demagnetized particles enter the magnetic field of the existing magnetic separators, they are magnetized and form floccules, in which rock particles are trapped.
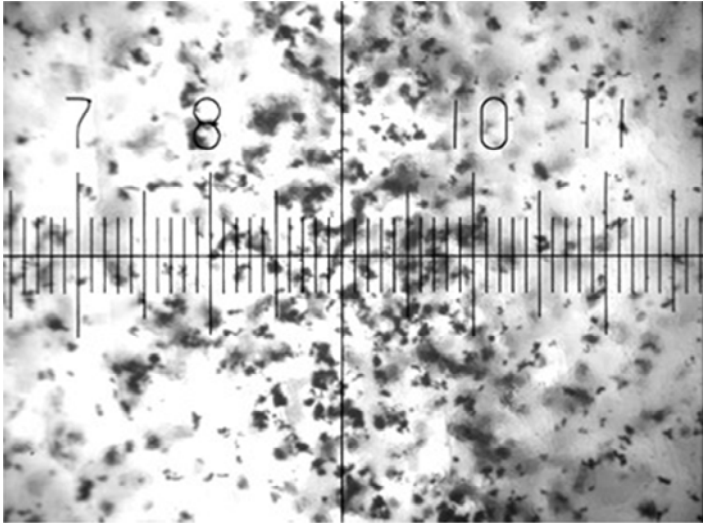
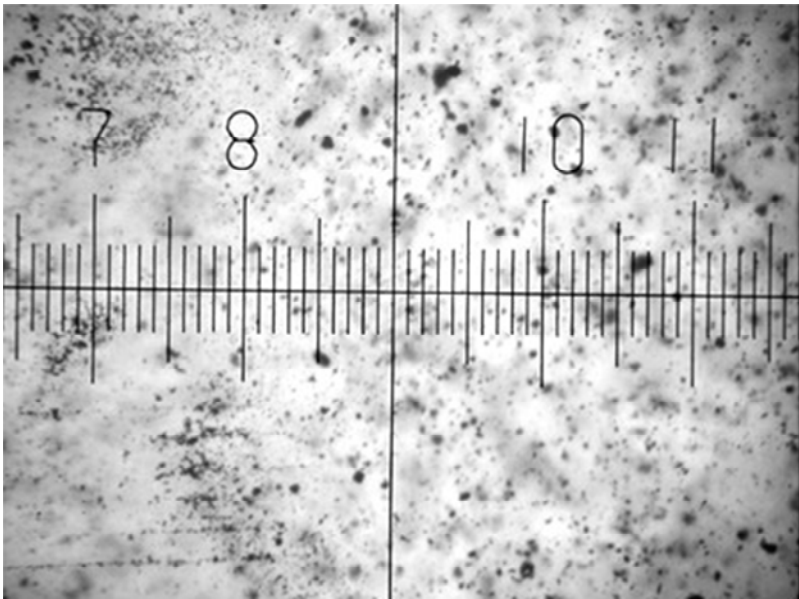**Fig. 5.** Particles of suspension, demagnetized in the field of 20 kHz

Fig. 6. Particles of suspension after treatment with a 70 kHz field

Accordingly, the quality of concentrate deteriorates. To prevent quality deterioration, it is necessary to separate demagnetized particles either by non-magnetic methods, e.g. by flotation, or in magnetic separators with an alternating high-frequency magnetic field.

Conclusions

- Until now, there are no devices for complete demagnetization of fine particles of the ferromagnetic material in the suspension flow.
- Demagnetization of such type can be carried out in high-frequency magnetic fields with induction amplitude greater than the residual magnetization of magnetite particles.
- Demagnetization of ferromagnetic particles before their further non-magnetic separation can provide indices of the concentrate quality, close to the theoretically possible ones.

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