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THE IMPACT OF A MAGNETIC FIELD ON THE WEAR OF THE GRINDING BODIES, LINING, AND ORE DISINTEGRATION

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Research aims *to analyze the effects of a magnetic field on ore disintegration processes: the improvement of mineral disclosure selectivity when grinding iron ore and wear reduction of the grinding bodies and lining.*
Research methodology. *The study of a magnetic field topography and parameters, depending on the position and the characteristics of magnets embedded into the lifter bars. Full-scale modeling of a magnetic field topography has confirmed the possibility of implementing physical preconditions for the creation of a magnetic field in the space between the lifter bars.*
The analysis results *have shown that the physical models reflect the impact of the magnetic field, disintegration indicators, and the grinding bodies wear reduction in a grinding mill adequately. It has been stated, that in the variety of engineering solutions for the creation of a magnetic field in the ball charge, embedding magnets into the lifter bars of a lifter-bar lining is the easiest variant. The variant of the lifter bar lining has been suggested, which makes it possible to create the induced magnetic field in a zone of contact between the grinding bodies and the lifter bars and between the grinding bodies.*
Research results are to be applied *in the processes of ore grinding in ball mills. Some schemes of embedding constant magnets into the lifter bars have been suggested allowing to solve the assigned task of wear reduction of the grinding bodies. It has been shown, that such traditional economic indicators as the net present value (NPV), the internal rate of return (IRR), the profitability index (PI), and a simple and discounted payback periods ensure the effectiveness of an investment project as early as one set of magnet lifter bars realization.*

Key words: *disintegration; magnetic field; wear; grinding bodies; lifter bar.*

The impact of the magnetic field on the processes of ore disintegration in ball mills. The analysis of the magnetic field impact on the processes of ore disintegration has revealed the following effects: the improvement of mineral disclosure selectivity when grinding iron ore and wear reduction of the grinding bodies and lining. The physical model of iron ore breaking in a magnetic field can be presented in the following way. Induced by the external magnetic field, grinding bodies magnetization causes the appearance of a magnetic force $F_{м} = M_{ч}\mathrm{grad}H \approx d^{3}$ which "draws in" the particles containing magnetic minerals into the zone of grinding bodies contact, where H – magnetic field intensity, A/m; $M_{ч}$ – magnetic moment of particles, $A \cdot m^2$; d – particle size, m. As the result of such interaction, mainly the fragments requiring disclosure and concentrating in the space between the balls are collected in the zone of breaking. In addition to the magnetic forces, the particles sustain the resistance force of the disintegrated medium $F_{с} \approx (dV_{ср})^{n}$, n = 1–2, the parameter which is dependent on the size of particles d, m, and their displacement velocity $V_{ср}$, m/s. Under the action of the indicated forces, mainly large particles possessing higher magnetic moment $M_{ч}$,

i. e. clusters or large particles of a magnetic mineral, get into the zone of grinding bodies contact. Minor disclosed particles of an ore mineral and the non-magnetic particles either do not break up or slightly break up at random. Selective breaking (being selective in relation to the fragments containing magnetic mineral) becomes possible due to two competitive forces: magnetic attraction and an opposing resistance force of the moving medium (pulp and ball charge). The indicated interaction creates the preconditions for selective (in relation to the size and magnetic properties) breaking of the components containing magnetic minerals. Comparative tests over some varieties of iron ore have revealed the influence of pulp density, the modes of the material unloading (mill discharge level), magnetic field parameters in the ball charge, and the characteristics of the disintegrated material. The results of the technological experiments (within the continuous cycle with a magnetic separator) have confirmed the selective character of magnetic field impact: the indicators of mineral disclosure are improved and grinding productivity is increased by 1.4–2.8 times (depending on the grain size of the disintegrated material). The increase in the mass fraction of iron in the concentrate under its significant reduction in tailings (in some cases up to 4–6%), increased output of the concentrate, and the increase in the level of magnetite disclosure selectivity by 38.3–90.8% (according to the data of mineralogical investigations) also testify to the selectivity of magnetic field impact on grinding indicators [1].

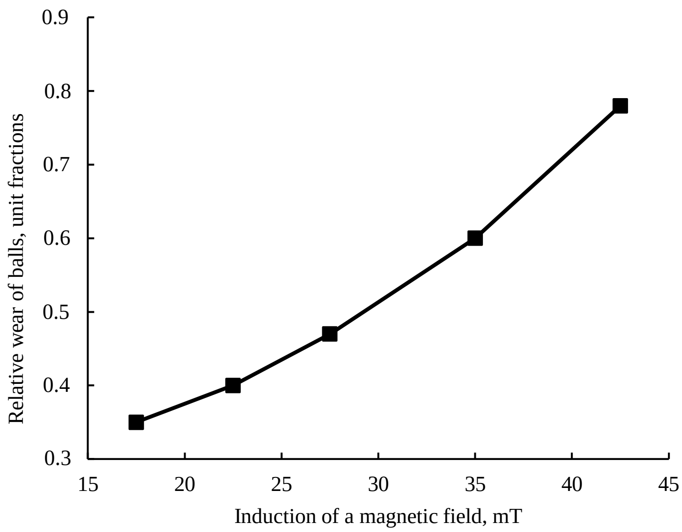

Fig. 1. The dependence between the relative reduction of wear of balls and induction of a magnetic field in a mill

Рис. 1. Зависимость относительного снижения износа шаров от индукции магнитного поля в мельнице

In the course of the indicated research the study of the influence of a magnetic field on grinding bodies wear under various parameters of a magnetic field have been carried out. Laboratory studies of grinding bodies wear in a mill with a magnetic field have shown the reduction of wear by 15–50% depending on the stage of grinding and the type of ore. Fig. 1 reveals the dependence between the relative decrease of balls wear and magnetic field induction. However, the proven effectiveness of magnetic fields impact on ore grinding processes haven't led to the discovery of new equipment mainly for the lack of any simple and reliable engineering solutions for the creation of a magnetic field of the necessary topography and required induction in a mill's grinding space.

Another example of magnetic fields application in ball mills is a rubber-magnetic lining of *Skega Orebed®* type developed to improve the productivity of mills, primarily for the second and third stages [2]. In general, lining represents bars made of abrasion-resistant rubber with embedded constant magnets which ensure boltless fastening of lining on the surface of a drum. Besides, open magnetic stray fluxes create magnetic forces attracting magnetic particles formed by the scrap of the grinding bodies and magnetic minerals to the external surface of lining. The created "ore bed" protects rubber lining from wear. In the linings of a similar nature, stray magnetic field of the embedded magnets almost completely closes through the mill's drum and the "ore bed". On the external surface of the "ore bed" magnetic forces weaken and stop keeping magnetic particles, which limits the thickness of a bed and ensures its renewal. At the same time, the given factor almost completely excludes the possibility of grinding bodies magnetization and the creation of a magnetic field with the necessary parameters between the balls. Operation experience of rubber-magnetic linings similar to *Orebed*™ bars has confirmed the increase of their service live as compared to the metallic lining [2, 3]. Despite the costs for the re-lining of rubber-magnetic elements are almost 2–3 times lower than for the lining with bolt fastening, low frequency of operations on the replacement of the abrasive-resistant lining (once in 3–5 years) eliminates the significance of the given effect for the investor. As the analysis has shown, more significant effect of magnetic field impact in relation to investments is the reduction of grinding bodies wear and the increased intensity of the processes of disintegrating ore which contains magnetic minerals. Positive results of magnetic field impact make the search for the solutions allowing to fulfill several tasks in an integrated manner relevant: to reduce the wear of lining and the grinding bodies, and improve mineral disclosure effectiveness by means of magnetic field impact on disintegration processes.

The substantiation of the lifter bar structures with embedded magnets. According to the main provisions of tribology, the intensity of the surface wear at grinding is in many ways determined by the sliding velocity of the contacting bodies, the value of the materials specific pressure on the lining, and friction between the medium and the lining [4–8]. Thus, in order to reduce wear it is necessary to reduce or eliminate the sliding movement of the ball charge towards lining, reduce contact pressure and the coefficient of friction. It should be noted, that sliding value reduction leads to specific energy consumption reduction, because sliding of the ball charge against the drum causes the need in the increase in its rotation speed by the amount of slippage, and the increase in the power consumption. Pressure can be reduced by means of increasing the contact area by virtue of the formed "soft lining" with simultaneous decrease in the coefficient of friction between the lining and the balls. The role of lubricant in this case is performed by a suspension of finely powdered fractions of magnetic minerals and scrap. Magnetic field induced by the grinding bodies concentrates magnetic particles (scrap, magnetic minerals, etc.) in the zone of balls contacts; the magnetic particles perform protective function and reduce balls wear. To the fullest extent, this effect is manifests during iron ore grinding [1]. Frame-by-frame analysis of balls movement dynamics in a mill with the superimposed magnetic field has shown that near the surface of a drum the balls move almost without mutual slippage. The corresponding arrangement of magnets keeps the balls in the space between the lifter bars owing to magnetic interaction and prevents slippage.

The basis for the suggested engineering solution is formed by the interaction of magnetic materials with an external magnetic field. Physical precondition for the given task fulfillment is multiple increase in magnetic field induction between the balls and in the zone of balls contact with the surface of a lifter bar with an embedded magnet. In the case under consideration, the grinding bodies themselves serve as magnetic flux concentrators, creating a magnetic field of high intensity with a high gradient in the clearance between the balls. For example, if in the absence of the balls magnetic field induction on the surface of a lifter bar is 0.038 T, then between the balls it increases up to 0.38 T and more. The upper limit of magnetic field induction on the surface of a lifter bar is limited by the condition of prevention of the true contact between the ball charge and lining and is determined by the ration of the ball's gravity force in the separation point and the attraction force of magnetic material in inhomogeneous magnetic field: $F = M\text{gradH} = \mu\mu_o V\text{HgradH}$, where M – magnetic moment of magnetic material; gradH – gradient of magnetic field intensity; V – magnetic material volume (ball, scrap or ore magnetic particle), m^3; μ, μ_o – magnetic permeability of magnetic material and vacuum, N/A^2. Magnetic field parameters can be chosen out of the following condition depending on the type of a mill

$$(2\pi n)^2 Rm + \mu\mu_o V\text{HgradH} > P\cos\varphi, \qquad (1)$$

where P – ball's gravity force, N; φ – ball's separation angle, degrees; R – drum's radius, m; n – rotational speed, r/min; m – balls' mass, t.

The indicated condition for the mills of the second and third stage of grinding (with a diameter of approximately 3–4 m) can be met under the use of the magnets with induction 0.38–0.40 T under the design thickness of a rubber layer of a lifter bar.

The solution to the stated task reduces to the search for the ways of inducing magnetic field in a zone of balls interaction with the lining and the disintegrated material, for example, by means of embedding constant magnets into the lifter bars of a ball mill. The corresponding choice of magnetic field intensity gradient and induction value (on the surface of a lifter bar) is able to create the conditions under which the layer of balls will protect the lifter bars and lining from abrasive wear caused by grinding bodies slippage against the lining and the lifter bars. The suggested structure of lifter lining allows to create an induced magnetic field between the grinding bodies and the lifter bars in a relatively simple way. The lifter bars are usually made of polymeric materials, rubber, for example, however, in the solutions under consideration the use of bonded magnets is possible as the material for the lifter bar or for various magnetic insertions. Engineering implementation of the lifter bars with the embedded magnets in the lifter-bar lining depends on the type of a mill, disintegrated ore, and the stage of disintegration. Embedding constant magnets into the operating lifter bars as embedded elements in the existing press molds is the most structurally simple solution to the given task. However, these simple solutions do not exclude the creation of completely different structures of lifter bars which generate magnetic flux in the ball charge in the optimal way. Structural arrangement of magnets in the lifter bar is chosen with the account of the fact that the force of interaction is determined not only by the magnetic field intensity sufficient to induce the magnetization of balls and other particles, but also by the size of its gradient.

The advantage of the lifter bars structure with the embedded magnets is grinding bodies, lifter bars, and lining wear reduction, which is achieved by creating a magnetic field in the space between the balls and a gradient of a magnetic field on the surface of the lifter bars, which prevents slippage of the ball charge contacting the lining. The technical aspects of the given structure development reduce to the choice of an arrangement scheme of magnets in the lifter bars, the creation of maximum magnetic field gradient in the space between the magnets, and provision with the desired value of magnetic field induction on the surface of the lifter bars. As soon as magnetic field in the system *lifter bar–ball charge–lining plate* is a protective factor for the lifter bars and grinding bodies from wear, it is necessary to be aware of the topography of balls induced magnetic field at their entering the zone of magnetic flux impact between the lifter bars. Physical modelling of the magnetic field topography has confirmed the possibility to implement the conditions mentioned above to create a magnetic field in the space between the lifter bars. In the course of the research, some variants of magnets structural arrangement in the lifter bar have been considered. The topography of magnetic field induction for a model of two lifter bars at a distance of 210 mm from each other (which is compared to their arrangement in a mill) is introduced at fig. 2. Flat barium ferrite magnets (80 x 60 x 14 mm) with induction on the surface 30–60 mT were used as magnets; at end surfaces induction was 100–110 mT. For ease of induction measuring, in one plane grinding bodies were fashioned with 42 mm diameter disks. Magnetic induction in the simulated space is marked by the numbers near the extension line. It should be noted that the higher gradient of induction in the space *ball–plane* is 2.5–4 times higher than the gradient of induction in the space between the planes of magnets, which provides conditions for the implementation of the desired forces of interaction between the balls and other magnetic materials in the space between the balls. This circumstance is an important factor for balls wear reduction by means of lubricant producing out of the fine particles of the magnetic material. The measurement have shown that induction of magnetic field between the balls can reach 240–250 mT under field induction on the surface of the magnet being about 30 mT.

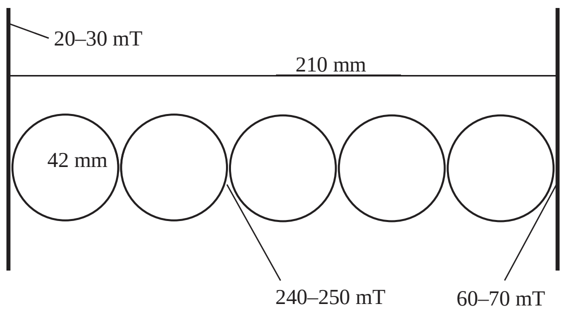

Fig. 2. The arrangement of the grinding bodies between the lifter bars
Рис. 2. Расположение мелющих тел между лифтерами

To protect the lifter bar from wear according to condition (1) it is necessary to create magnetic field induction in the zone of ball charge action, sufficient for the magnetization of balls, magnetic minerals aggregates, scrap, and other magnetic materials in a mill. At the same time, there is the task of protecting ceramic magnets from breaking by means of creating a protection layer. The choice of thickness of the lifter bar layer above the magnet is conditioned by the need for its protection and the creation of the induction on the surface of a lifter bar sufficient for the magnetization of balls (and other magnetic materials). Optimum thickness of a protective layer is chosen on the basis of the dependence between magnetic field induction and the distance above the magnet. Experimental estimation of magnetic field induction variation with the growth of the distance x from the surface of the magnet allowed to describe the given dependence using the equation $B(x) = 9.97 + 63.8/[1+0,62\exp(0.067x)]$, the coefficient of determination is $R^2 > 0,99$.

When constructing the magnetic system embedded into the lifter bars, it is important to use any possibilities to increase induction and gradient of a magnetic field, for example, arrange magnets at a magnetically conductive metal plate. Estimations show, that induction on the surface of the magnets situated on the magnetically conductive metal plate are by 30–40% higher than without it, and the gradient of magnetic induction in the space between the magnets on the metal plate increases by several times.

Applications of magnets in typical structures of the lifter bars are introduced at fig. 3 (at one lifter bar the two variants of embedding the magnets are presented). The principles of magnets embedding and arrangement are the same for both typical and newly developed lifter bars. Variant 1 at fig. 3 with a trapezoidal-shaped fixing plug allows to use, for example, magnetoelastic material to increase induction of a magnetic field as compared to a rubber plug and to use materials with physical-mechanical characteristics which reduce wear and impact load on a magnet [9–12]. The size and the type of constant magnets are determined by the structure of a lifter bar and the system of its interface with a rubber lining plate.

In modern practice, two groups of ferrite magnets are used as constant magnets: Nd–Fe–B-based and Ba–Sr-based. As long as Ba–Sr magnets are almost by an order of magnitude cheaper than niobium magnets, the choice of the structures and the type of magnets embedded into the lifter bar is determined by the ratio between engineering and economic indicators. Magnets based on barium and strontium oxides have become widely used due to their cheap price and possibility to be applied at temperatures up to +280 °C. Magnets based on Nd–Fe–B have got high values of residual induction around 0.7–1.3 T, and coercive force by magnetization within the limits of 1–2 MA/m. Thus, the creation of the lifter bars with magnetic induction on the external surface of 100–150 mT (without the ball charge) does not cause any engineering problems.

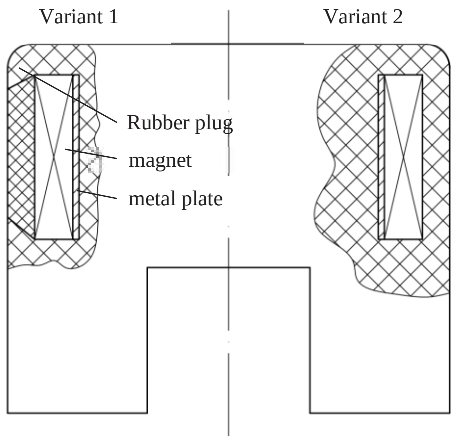

Fig. 3. The variants of embedding magnets into the lifter bar
Рис. 3. Варианты встраивания магнитов в лифтер

Results analysis. The lining developers have to take into account a number of factors: operational characteristics, service life, price and costs ratio, maintenance simplicity and frequency, current market prices, etc. The effectiveness of the innovative solution is determined according to the traditional criteria of investment projects: the net present value (NPV), the internal rate of return (IRR), the profitability index (PI), and a simple and discounted payback periods. Results analysis shows that basic investment indicators: NPV – RUB3704.3 thousand, IRR – 60,4%, PI – 2,2, and 18 months payback period are thoroughly acceptable for such projects. It should be noted, that given estimations have been derived from the calculation of one set realization: investment in one set is RUB3000 thousand at sales revenue of RUB2500 thousand and 15% discounting rate. Increased quantity of sets significantly reduces the payback period: investment for the second set of lining is repaid almost at once, as long as basic expenses have been entered at the realization of the first set. The given indicators have been obtained under minimum balls wear reduction (less than 5%), which reduces the risks of the initial stage of investment. At grinding bodies wear reduction up to 10–50% (actually received on trials) the indicators of investment project effectiveness increase. The account of revenue from mills productivity increase by means of reducing downtime for lifter bars and lining replacement, as well as the account of improving indices of iron ore disintegration will also allow to improve the effectiveness of the suggested solution.

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ВЛИЯНИЕ МАГНИТНОГО ПОЛЯ НА ИЗНОС МЕЛЮЩИХ ТЕЛ, ФУТЕРОВКИ И ДЕЗИНТЕГРАЦИЮ РУД

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Цель работы. *Анализ эффектов воздействия магнитного поля на процессы дезинтеграции руд: увеличение селективности раскрытия минералов при измельчении железных руд, снижение износа мелющих тел и футеровки.*
Методология исследования. *Изучение топографии магнитного поля и его параметров в зависимости от расположения и характеристик магнитов, встраиваемых в лифтеры. Натурное моделирование топографии магнитного поля подтвердило возможность реализации физических предпосылок для создания магнитного поля в пространстве между лифтерами.*
Результаты анализа *показали, что физические модели адекватно отражают влияние магнитного поля на показатели дезинтеграции и снижение износа мелющих тел в мельнице. Установлено, что среди различных вариантов инженерных решений для создания магнитного поля в шаровой загрузке наиболее простым является встраивание постоянных магнитов в лифтеры плиточно-лифтерной футеровки. Предложен вариант плиточно-лифтерной футеровки, позволяющий создать индуцированное магнитное поле в зоне контакта мелющих тел с лифтерами и между мелющими телами.*
Областью применения результатов исследований *являются процессы измельчения руд в шаровых мельницах. Предложено несколько схем встраивания постоянных магнитов в лифтеры, позволяющих решить поставленную задачу снижения износа мелющих тел. Показано, что традиционные экономические показатели: чистый дисконтированный доход (NPV), внутренняя норма доходности (IRR), индекс доходности (PI), простой срок окупаемости и дисконтированный срок окупаемости – обеспечивают эффективность инвестиционного проекта уже при реализации одного комплекта магнитных лифтеров.*

Ключевые слова: *дезинтеграция; магнитное поле; износ; мелющие тела; лифтер.*

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