Assessment of effect of lining material on energy efficiency of starting up ball mills

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Abstract. The article presents the possibility of increasing the service life of mill lining. Special attention is paid to the use of rubber linings for mills. A mathematical model of the asynchronous motor of ore grinding mills has been developed, i.e., the moment of resistance is shock. A system of equations for a synchronous motor of a mill plant for the d and q axes is described. Based on mathematical modeling of mill plant operating modes, it was determined that the corrosion coating prolongs the mill's service life, and the transition time is reduced to 10%.

1 Introduction

Grinding is one of the main technological processes of concentration plants. Being a very energy-intensive process that forms the final indicators of the beneficiation process, grinding determines the factory's technological, technical, and economic indicators. The results of all further processing of the enriched product depend on the grinding performance, first of all, such as the productivity of the plant, the extraction of a valuable component, its content in the concentrate, and losses in the tailings.

Crushed ore 10-30 mm in size is fed to drum (ball and rod) mills for grinding. When the drum rotates, the grinding medium (balls, rods, pieces of ore) and the medium to be ground rise to a certain height and then slide, roll or fall down. Grinding occurs due to the impact of the falling grinding medium, crushing, and friction between the rolling layers of the mill's contents. The movement of material along the drum occurs from the difference in loading and unloading levels: in wet grinding, the material is transported by water, and in dry grinding - by air flow. The design types of drum mills differ in the type of grinding bodies, the shape of the drum, and methods of grinding and unloading the crushed product.

In mill installations, the lining is the main unit on which the economy and efficiency of the technological process and its indicators depend. The operating experience has shown that the consumption of the lining material is influenced by its design parameters. In turn, the operating modes of the crushing medium, all other things being equal, determine the productivity and efficiency of material grinding in a ball mill. Therefore, any measures aimed at reducing the consumption of linings and crushing medium per ton of crushed

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product, as well as measures to increase the productivity and efficiency of crushing units, will affect the effectiveness of the entire metallurgical complex.

2 Literature Review

The development of mill lining systems led to the fact that manufacturing plants began to engage not only in the selection of materials for their manufacture but also in improving the design of the lining to ensure optimal characteristics of the grinding process.

The article [1] discusses various types of mill linings included in the range of products manufactured by Metso. Detailed descriptions of cost-effective mill lining systems for any grinding task: metal lining, rubber lining, Poly-Met combined rubber-metal lining, Orebed magnetic lining, discharge lining (discharge grids, discharge elevators, cone, trunnion). The adopted methodology for designing mill lining systems, a program for modeling the trajectory of the balls falling, are considered, and calculations of the volume of the mill and the service life of various lining options are given.

Yastrebov et al. [2] studied the characteristics of drum mills was carried out. The dependence on the waterfall mode of operation of the ball mill is indicated. The power consumed by drum mills to bring its load (balls, rods, ore) into the working condition has been calculated. Several formulas have been proposed for calculating the useful power and energy consumption of drum mills in various modes of their operation. In the case of using the addition of balls, their loaded volume has an insignificant effect on the increase in power. This can be explained by a change in the density of the load and a shift in its center of gravity. Based on the performed analysis, the correlation dependence between the power consumed by the grinding medium and the filling factor of the mill drum was determined. The likelihood of achieving maximum equipment performance increases with the optimal balance of power consumption and duty cycle.

Levchenko et al. [3] found that the combination in the structure of chromium-manganese alloys of the transition (1.6-2.2% C) class of the type 200G4X5L, 200G5X2L (200G5X2TFL) a sufficient amount of solid carbide phases and a plastic austenite-pearlite matrix provides the observed high indicators of their shock-abrasive and shock-abrasive-corrosion resistance. The efficiency of using wear-resistant alloys 200Г4Х5Л and 200Г5Х2ТФЛ as inserts of combined rubber-metal linings of drum mills for grinding iron ore was shown. Levchenko et al. [4] The efficiency of joint use of elastomers (rubbers) and wear-resistant steels and cast irons for mining and metallurgical equipment: mill linings, hydrocyclones, modular sieves, belt-conveyor screens, crushers, etc. were investigated. Rubber absorbs shock loads, damping them, thereby preventing the destruction of high-hard ware-resistant steels and cast irons. Studies have established that the combination in the structure of chromium-manganese alloys of the transition (1.6-2.2% C) class of the type 200G4Kh5L, 200G5Kh2L (200G5Kh2TFL) of a sufficient amount of solid carbide phases and a plastic austenitic-pearlite matrix provides high performance of their shock-abrasive and shock-abrasive-corrosion resistance. Transition alloy composite rubber-metal liners are effective.

3 Results and Discussion

To assess the effect of the lining material of ball mills on energy-efficient start-ups, we have carried out certain studies in this direction. It is known that the lining material for mills is mainly of two types: metal and rubber. Using the example of a ball mill MShTs with a motor, the effect of linings on start-up on an energy-efficient operating mode was assessed. The technical characteristics of the DSE-260 / 49-32 engine are given in Table 1.

Table 1. Passport data of the mill unit

Parameter	**Value**
Power, P, kW	1250
Stator voltage, U, B	6000
Rotor voltage, U, B	95
Stator current, I, A	140
Rotor current, I, A	270
Power factor, cos φ	0.9
Efficiency %	92.5
Rotation frequency, rpm	187.5

According to literature, when dry contact takes place at the initial moment of starting the mill, the static coefficient of sliding friction of the steel trunnion on the babbitt of the bearing housing is f_0 = 0.210. In the steady state of operation, the dynamic coefficient of friction is f = 0.013 - 0.024.

The total moment of friction in bearings is determined by the formula

$$M_{\text{тр}} = f(N_1 + N_2)R_{\text{c}}, \quad (1)$$

where N_1, N_2 are loads perceived by bearings; Rc is the radius of the drum journals.

It can be seen from the formula that a decrease in the loads taken by the bearings leads to a decrease in the friction torque also by 1.2 - 1.1 times. In addition, the starting conditions are facilitated since the initial value of the friction moment decreases, equal to

$$M_{\text{тр}_0} = f_0(N_1 + N_2)R_{\text{c}}. \quad (2)$$

To estimate the energy consumption for friction in bearings, we note that the power expended on friction is equal to $P_{\text{тр}} = M_{\text{тр}}\omega_{\text{б}}$, where $\omega_{\text{б}}$ is the angular speed of rotation of the drum.

Calculations for several drum mills equipped with dynamic plain bearings show that the frictional power losses in the bearings are on average 5.5% of the power consumed by the mill.

Thus, the annual energy consumption for friction in the main bearings is

$$E_{\text{тр}} = kM_{\text{тр}}\omega T_{\text{г}}, \quad (3)$$

where k is the equipment utilization factor; Tg is the number of hours per year.

For example, for a mill with a power of 1250 kW and ω= 1.06 s^{-1} at k = 0.9, the annual energy consumption for friction in bearings is

$$E_{\text{тр}} = kP_{\text{тр}}T_{\text{г}} = 0.9 \cdot 0.055 \cdot 2000 \cdot 8760 = 542025\ kW \cdot h.$$

Using a rubber lining will reduce the load on the bearings and, accordingly, the frictional energy losses by 1.2 - 1.1 times, which will save ΔE_{tr} = 108405.

Direct start-up of the mill motor presents certain difficulties, especially in conditions of limited power supply networks. The use of rubber lining facilitates starting conditions.

The equation of motion of the mill during its acceleration can be approximately described by the equation$I_{\text{п}}\varepsilon = M_{m.s.}(1 - k)$, where I_n is the moment of inertia of the rotating parts of the mill reduced to the rotor shaft; ε - angular acceleration of the engine rotor

$$k = M_{s.s}/\mathrm{M}_{m.s.} \tag{4}$$

where $M_{s.s\cdot}$, $M_{m.s.}$ are respectively, the average values of the engine torque and resistance torque.

The reduced moment of inertia is

$$I_{\text{п}} = I_{\text{p}} + I_{\text{б0}}/u^2 + I_{\text{з}}/u^2, \tag{5}$$

where I_p, I_{b0}, I_z are moment of inertia of the rotor, empty drum, and loading, respectively; u is gear ratio.

Calculations show that for gearless drives$I_{\text{б0}}^{\text{m}}/u^2 \approx I_{\text{p}}$; the ratio of the moment of inertia of the loading to the moment of inertia of the empty drum is$I_{\text{з}}/I_{\text{б0}}^{\text{m}} = 0{,}2$ ($I_{\text{бо}}^{\text{m}}$is the moment of inertia of the empty drum with a metal lining); the ratio of the moments of inertia of an empty drum with a metal and rubber lining$I_{\text{бо}}^{\text{m}}/I_{\text{бо}}^{\text{p}} \approx 1{,}5$.

Thus, the reduced moment of inertia for mills with metal and rubber lining is equal to

$$I_{\text{п}}^{\text{m}} = I_{\text{p}} + I_{\text{б0}}^{\text{m}}/u^2 + 0{,}2I_{\text{б0}}^{\text{m}}/u^2 = 2{,}2I_{\text{p}}, \tag{6}$$

$$I_{\text{п}}^{\text{p}} = I_{\text{p}} + I_{\text{б0}}^{\text{m}}/1{,}5u^2 + 0{,}2I_{\text{б0}}^{\text{m}}/u^2 = 1{,}8I_{\text{p}}. \tag{7}$$

From the above formulas, it is seen that

$$I_n^{\text{m}}/I_n^{p} = 1.2. \tag{8}$$

Then, for a rubber-lined mill, the equation of motion during the engine start-up period will have the form

$$I_{\text{п}}^{\text{m}}\varepsilon = 1.2M_{\text{dv.av}}(1-k) \tag{9}$$

Considering that$\varepsilon = d\omega/dt$, from the considered equation, it is possible to obtain the acceleration time of the engine of a mill with a rubber lining

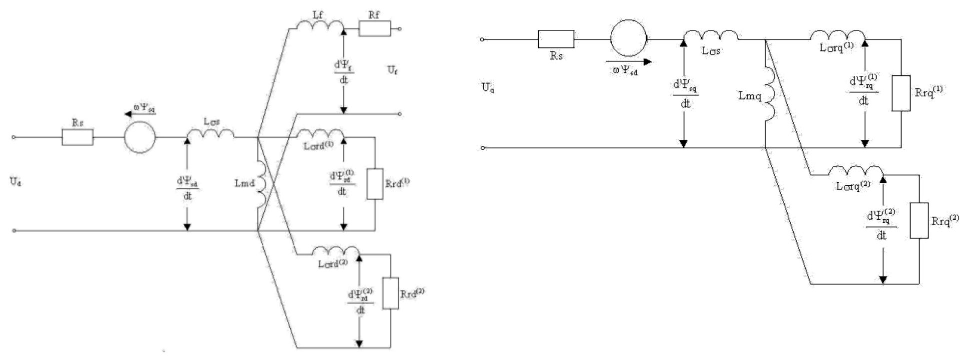
$$t_1 = \omega_{\text{y}} I_{\text{п}}^{\text{m}}/1.2\mathrm{M}_{\text{dv.av}}(1-k). \tag{10}$$

The influence of the dynamic parameters of a drum mill can be considered most fully on the basis of an adequate mathematical model, where transient processes in a synchronous motor are described by the complete Park - Gorev equations [5-8]

$$\left.\begin{aligned}
U_{id} &= i_{id}\cdot R_s + p\Psi_{sd} - \omega\cdot\Psi_{sq};\\
U_{iq} &= i_{iq}\cdot R_s + p\Psi_{sq} + \omega\cdot\Psi_{sd};\\
U_f &= i_f\cdot R_f + p\Psi_f;\\
0 &= i_{rd}^{(1)}\cdot R_{rd}^{(1)} + p\Psi_{rd}^{(1)};\\
0 &= i_{rd}^{(2)}\cdot R_{rd}^{(2)} + p\Psi_{rd}^{(2)};\\
0 &= i_{rq}^{(1)}\cdot R_{rq}^{(1)} + p\Psi_{rq}^{(1)};\\
0 &= i_{rq}^{(2)}\cdot R_{rq}^{(2)} + p\Psi_{rq}^{(2)}.
\end{aligned}\right\} \tag{11}$$

Here i_{sd}, $i_{rd}^{(1)}$, $i_{rd}^{(2)}$, Ψ_{sd}, $\Psi_{rd}^{(1)}$, $\Psi_{rd}^{(2)}$, i_{sq}, $i_{rq}^{(1)}$, $i_{rq}^{(2)}$, Ψ_{sq}, $\Psi_{rq}^{(1)}$, $\Psi_{rq}^{(2)}$ are the components of the current vectors and flux linkages of the stator and rotor contours,

respectively, along the d and q axes; i_f, Ψ_f are current and flux linkage in the excitation winding; R_s, R_f, $R_{rd}^{(1)}$, $R_{rd}^{(2)}$, $R_{rq}^{(1)}$, $R_{rq}^{(2)}$ are active resistance of the phase of the stator winding, field winding, as well as the resistance of the rotor circuits, respectively, along the d and q axes; $\omega$is the rotor speed.
The equivalent circuit of a synchronous motor in the d and q axes is shown in Fig 1 [5-11].



(a) *(b)*

Fig. 1. Equivalent circuit of a synchronous motor along the d (a) and q (b) axes.

Based on the equivalent circuit, we obtain the following equation for a synchronous motor:

$$\left.\begin{array}{l}
i_{md} = i_{sd} + i_f + i_{rd}^{(1)} + i_{rd}^{2};\\
\Psi_{md} = L_{md} \cdot i_{md};\\
\Psi_{sd} = L_{\sigma s} \cdot i_{sd} + \Psi_{md};\\
\Psi_{rd}^{(1)} = L_{\sigma rd}^{(1)} \cdot i_{rd}^{(1)} + \Psi_{md};\\
\Psi_{rd}^{(2)} = L_{\sigma rd}^{(2)} \cdot i_{rd}^{(2)} + \Psi_{md};\\
\Psi_f = L_{\sigma f} \cdot i_f + \Psi_{md}.\\
i_{mq} = i_{sq} + i_{rq}^{(1)} + i_{rq}^{2};\\
\Psi_{mq} = L_{mq} \cdot i_{mq};\\
\Psi_{sq} = L_{\sigma s} \cdot i_{sq} + \Psi_{mq};\\
\Psi_{rq}^{(1)} = L_{\sigma rq}^{(1)} \cdot i_{rq}^{(1)} + \Psi_{mq};\\
\Psi_{rq}^{(2)} = L_{\sigma rq}^{(2)} \cdot i_{rq}^{(2)} + \Psi_{mq}.
\end{array}\right\} \qquad (12)$$

Here Ψ_{md}, Ψ_{mq}, i_{md}, i_{mq} are the flux linkages and currents of the magnetization branch, respectively, along the d and q axes; L_{md}, $L_{\sigma rd}^{(1)}$, $L_{\sigma rd}^{(2)}$, L_{mq}, $L_{\sigma rq}^{(1)}$, $L_{\sigma rq}^{(2)}$ are the leakage inductance of the magnetization branch and the rotor contours, respectively, along the d and q axes; $L_{\sigma s}$, $L_{\sigma f}$ are leakage inductance of the stator and field winding [12-17].

Having determined from expressions (12) the values of the currents

$$\left.\begin{array}{l}
i_{sd} = \frac{\Psi_{sd}-\Psi_{md}}{L_{\sigma s}};\ i_{sq} = \frac{\Psi_{sq}-\Psi_{mq}}{L_{\sigma s}};\ i_f = \frac{\Psi_f-\Psi_f}{L_{\sigma f}};\\
i_{rd}^{(1)} = \frac{\Psi_{rd}^{(1)}-\Psi_{md}}{L_{\sigma rd}^{(1)}};\ i_{rd}^{(2)} = \frac{\Psi_{rd}^{(2)}-\Psi_{md}}{L_{\sigma rd}^{(2)}};\\
i_{rq}^{(1)} = \frac{\Psi_{rq}^{(1)}-\Psi_{mq}}{L_{\sigma rq}^{(1)}};\ i_{rq}^{(2)} = \frac{\Psi_{rq}^{(2)}-\Psi_{mq}}{L_{\sigma rq}^{(2)}},
\end{array}\right\} \qquad (13)$$

and substituting them into the equations for the components of the currents of the magnetization branch, we obtain the expressions:

$$\left.\begin{aligned}\Psi_{md} &= \frac{1}{B_d}\cdot\left[\frac{\Psi_{sd}}{L_{\sigma s}}+\frac{\Psi_f}{L_{\sigma s}}+\sum_{k=1}^{2}\frac{\Psi_{rd}^{(k)}}{L_{\sigma rd}^{(k)}}\right];\\ \Psi_{mq} &= \frac{1}{B_q}\cdot\left[\frac{\Psi_{sq}}{L_{\sigma s}}+\frac{\Psi_f}{L_{\sigma s}}+\sum_{k=1}^{2}\frac{\Psi_{rq}^{(k)}}{L_{\sigma rq}^{(k)}}\right];\end{aligned}\right\} \quad (14)$$

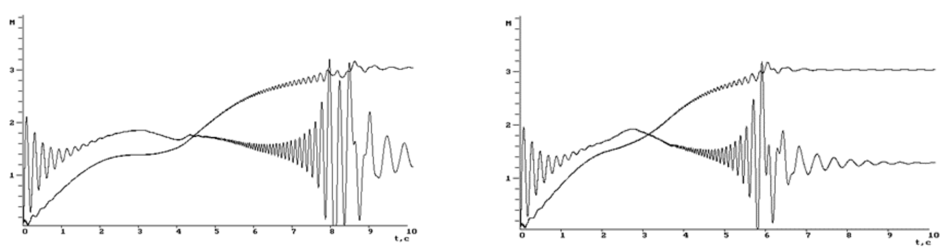
where $B_d=\frac{1}{L_{\sigma s}}+\frac{1}{L_{md}}+\frac{1}{L_{\sigma f}}+\sum_{k=1}^{2}\frac{1}{L_{\sigma rd}^{(1)}}$; $B_q=\frac{1}{L_{\sigma s}}+\frac{1}{L_{mq}}+\frac{1}{L_{\sigma f}}+\sum_{k=1}^{2}\frac{1}{L_{\sigma rq}^{(1)}}$ are the coefficients depending on the stator leakage inductances, magnetization branches, and rotor circuits.

The system of equations (10), taking into account (11) - (14), supplemented by the equation of the torque and the equation of motion of the drive, can be represented as follows:

$$\left.\begin{aligned}
&p\Psi_{sd} = U_{sd}-\frac{R_s}{L_{\sigma s}}\cdot(\Psi_{sd}-\Psi_{md})+\omega\cdot\Psi_{sq};\\
&p\Psi_{sq} = U_{sq}-\frac{R_s}{L_{\sigma s}}\cdot(\Psi_{sq}-\Psi_{mq})+\omega\cdot\Psi_{sd};\\
&p\Psi_{f} = U_{f}-\frac{R_s}{L_{\sigma s}}\cdot(\Psi_{f}-\Psi_{md});\\
&p\Psi_{rd}^{(1)} = -\frac{R_{rd}^{(1)}}{L_{\sigma rd}^{(1)}}\cdot\left(\Psi_{rd}^{(1)}-\Psi_{md}\right); \qquad p\Psi_{rd}^{(2)} = -\frac{R_{rd}^{(2)}}{L_{\sigma rd}^{(2)}}\cdot\left(\Psi_{rd}^{(2)}-\Psi_{md}\right);\\
&p\Psi_{rq}^{(1)} = -\frac{R_{rq}^{(1)}}{L_{\sigma rq}^{(1)}}\cdot\left(\Psi_{rq}^{(1)}-\Psi_{mq}\right); \qquad p\Psi_{rq}^{(2)} = -\frac{R_{rq}^{(2)}}{L_{\sigma rq}^{(2)}}\cdot\left(\Psi_{rq}^{(2)}-\Psi_{mq}\right);\\
&\Psi_{md} = \frac{1}{B_d}\cdot\left[\frac{\Psi_{sd}}{L_{\sigma s}}+\frac{\Psi_f}{L_f}+\sum_{k=1}^{2}\frac{\Psi_{rd}^{(k)}}{L_{\sigma rd}^{(k)}}\right];\\
&\Psi_{mq} = \frac{1}{B_q}\cdot\left[\frac{\Psi_{sq}}{L_{\sigma s}}+\sum_{k=1}^{2}\frac{\Psi_{rq}^{(k)}}{L_{\sigma rq}^{(k)}}\right];\\
&p\omega = \frac{p_1}{I}\cdot[M-M_c(\omega)];\\
&M = \frac{1}{L_{\sigma s}}\cdot\left(\Psi_{sq}\cdot\Psi_{md}-\Psi_{sd}\cdot\Psi_{mq}\right).
\end{aligned}\right\} \quad (15)$$

The resulting system of differential equations describes the transient processes of a synchronous motor in the d, q coordinate system [18-25].

Figures 2 a, b shows the calculated dependences of the angular velocity and torque in the drive shaft when starting the synchronous motor of the MShTs 4500--6000 mill with metal and rubber lining, which confirm the conclusions made above - the use of a rubber lining, in this case, made it possible to reduce start-up time 1.4 times.



(a) (b)

Fig. 2. Dynamics of the drive of the mill МШЦ 4500 × 6000 at start-up: a - a drum with a metal lining; b - a drum with a rubber lining; M electromagnetic torque of the engine; ω - angular speed of rotation.

4 Conclusion

These expressions allow us to conclude that the use of a rubber lining from the point of view of starting the engine is equivalent to an increase in the engine torque by more than 1.2 times (since the above expression does not take into account the reduction in friction losses in the main drum bearings).

This will make it possible to compensate for the decrease in MDP by supplying electric networks of limited power by more than 20% and to ensure a reliable engine start.

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