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Determining Energy Cost for Milling Solid Matter in a Ball Mill

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The article provides findings of analytical research into the process of milling friable matter in a ball mill. We have received an expression to determine energy cost of milling with the account of the method of milling and the characteristics of the material to be ground.
In the paper, the analytical results of bulk materials grinding process in a ball mill are presented. The differential equation is obtained whose solution determines the value of the grinding mode coefficient, corresponding to the maximum value of grinding process efficiency. The use of the introduced ball mill modes allows reducing the time spent on grinding by 28.9 % for cement clinker, 18.4 % for black coal, 28.9 % for marble and 19.6 % for rock salt compared to the traditionally recommended ones.

1. Introduction

Among the processes of many chemical industry branches a special emphasis is put on processes of bulk materials grinding. Extra attention to the materials refinement is provoked due to high power consumption and low efficiency of the process (Deniz, 2003). There is a big amount of grinding machines, among which ball mills are widely used due to the ease of operation and maintenance. However, a significant drawback of the grinding process by means of ball mills remains their low coefficient of efficiency (Bauer and Craig, 2008). Grinding process is characterized by chaotic movement of the grinding media (balls) and by a certain degree of uncontrollability of reproducible grinding results and as a consequence by decrease in energy efficiency of the grinding process. To solve this problem Ajaal et al. (2002) propose to apply a magnetic field to the ball mill. A worldwide survey on grinding mill circuits in the mineral processing industry (Wei and Craig, 2008) had been shown that main manipulated variables are the flow rate of water to the sump, the flow rate of water to the mill, the feed rate of solids to the mill, and the flow rate of the sump discharge slurry. But in the above publication does not show assess of the impact of changes in the parameters on the grinding process energy efficiency, while our article devoted to the solution of this issue. As pointed out (Hennart et al., 2009) the grinding mechanism depends on the orientation and intensity of the forces applied on the particles. The breaking parameters were used to determine the grinding mechanism at different grinding conditions. The aim of our research is to solve the problem of the determining methods of minimization of energy consumption for grinded bodies of different physical and chemical nature.

2. The calculation of ball mill rational mode

The main parameter that determines the mode of ball mill operation is drum rotation working velocity. The angular velocity of drum mill rotation ω is directly proportional to the grinding mode coefficient ψ:

$$\omega(\psi)=\psi\omega_{\kappa p}=\psi\sqrt{\frac{g}{R}} \quad (1)$$

where $\omega_{кр}$ is calculated value of the critical velocity according to the formula, s^{-1}; R is radius of the inner surface of the drum, m; g is acceleration of gravity, m s^{-2}; ψ is grinding mode coefficient, usually, according to the recommendations, is assumed equal to 0.75.

To evaluate the efficiency and intensification of the grinding process by selecting the most efficient ball mill operation mode it is necessary to formulate a functional dependence of the grinding process parameters.

Kuznetsova and Ved (2013a) presented new approach to the definition of grinding process power outputs is represented, which takes into account the relation of the impact crushing and grinding by friction. On this basis, a phenomenological model of ball milling is created, linking the parameters as follows: the geometry of the drum, the capacity rate, the drum load relation and distribution, the drum rotation velocity, geometrical and physical properties of the crushed material and the grinding process coefficient of efficiency. There is a parameter first introduced in the calculation which characterizes the fraction of the energy that falls on the chopping blow. The expression that determines the grinding process efficiency has the following form (Meshalkin et al., 2014):

$$\eta(\psi)=\frac{8\pi m_M\,\varphi}{E\rho\rho_K\,\omega(\psi)^3 R^2 t\left(1-k(\psi)^2\right)c(\psi)^2}\left(\sigma_{пр}^2\frac{1-p(\psi)^{10\,lg\frac{s_k}{s}+1}}{1-p(\psi)}+\sigma_m^2\left(1-p(\psi)^{10\,lg\frac{s_k}{s}}\right)\right) \quad (2)$$

where η is grinding process efficiency; ψ is grinding mode coefficient; $m_ш$ – the ball load mass, kg; m_M is crushed material mass, kg; c is velocity coefficient of the grinding media; R is inner surface radius of the drum mill, m; ω is rotation angular velocity of the drum mill, rad s^{-1}; E is crushed material elasticity modulus, Pa; ρ is crushed material density, kg m^{-3}; $\sigma_{пр}$ is material ultimate strength practical value, Pa; σ_m is ultimate strength theoretical value, Pa; s is specific surface of the material fed into the mill, m^2 kg^{-1}; s_k is ground material specific surface, m^2 kg^{-1}; p is the parameter characterizing the energy fraction that falls on the chopping blow; t is material grinding time, s; k is coefficient corresponding to the radius of the inner contour with respect to the radial load of the external circuit; φ is drum mill capacity rate.

The extremum of the presented function Eq(2), which describes the dependence of the grinding process, determines the velocity limit rotation of the ball mill drum, corresponding to the efficiency peak value of the process

$$\frac{d}{d\psi}\left(\frac{\sigma_{пр}^2\frac{1-p(\psi)^{10\lg\frac{s_k}{s}+1}+1}{1-p(\psi)}+\sigma_T^2\left(1-p(\psi)^{10\lg\frac{s_k}{s}+1}\right)}{\omega(\psi)^3\left(1-k(\psi)^2\right)c(\psi)^2}\right)=0 \quad (3)$$

The graphical representation of Eq(2) and (3) is represented by Figure 1.

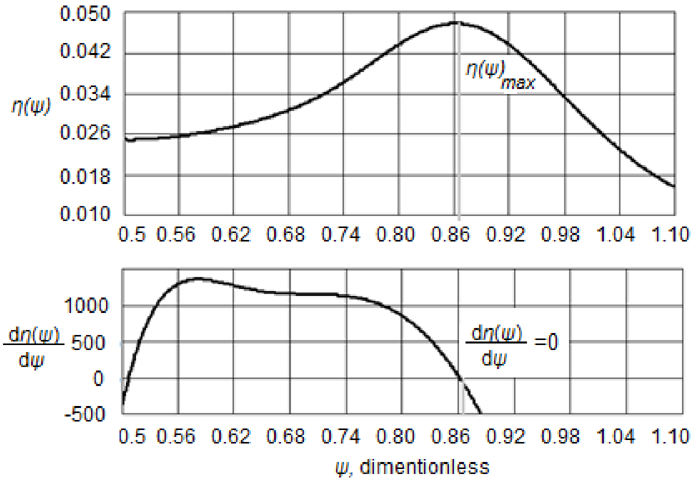

Figure 1: The relation of the efficiency (dimensionless), differential efficiency function (dimensionless) and the grinding mode coefficient (dimensionless)

The solution of the differential Eq(3) determines the grinding mode coefficient value ψ – the proportion of the critical velocity estimated values, which corresponds to the grinding process efficiency peak value.

3. The calculation of ball mill energy efficiency mode

For the practical application of the suggested grinding process model the parameter dependencies kinds of energy p and speed c of this process on the grinding mode coefficient ψ were experimentally determined.

$$p(\psi) = 0.2708\psi^3 - 1.1688\psi^2 + 1.2873\psi + 0.5607 \tag{4}$$

$$c(\psi) = -7.291\psi^3 + 56.563\psi^2 - 78.427\psi + 33.184 \tag{5}$$

Therewith it was taken into account that the grinding media velocity coefficient value c and the parameter value p depends only on the drum mill rotation mode that is on the grinding mode coefficient ψ.
For the grinding of solid matter like marble, according to the calculations by the Eq(3), the value of the grinding mode rational coefficient equals 0.861.
The energy efficiency implementation of the calculated rational grinding process velocity mode (ψ_1) compared with a mode that is suggested in the literature as the best one – (ψ_2), theoretically determined by the relation of energy consumption (E_1, E_2) and the grinding time *(t1, t2)* of these processes. The value of ψ_2 which recommended in the scientific literature is 0.75.
The relation of energy consumption for the implement of the compared modes is defined by the formula:

$$\varepsilon = \frac{E_1}{E_2} = \frac{\eta(\psi_2)}{\eta(\psi_1)} \tag{6}$$

The relation of the grinding time while implementing the modes, which are compared, is described by the formula:

$$T = \frac{t_1}{t_2} = \frac{\psi_2 \eta(\psi_2)}{\psi_1 \eta(\psi_1)} \tag{7}$$

The efficiency relation while implementing these modes is given by (Kuznetsova et al., 2014)

$$\Theta = \frac{\eta(\psi_1)}{\eta(\psi_2)} \tag{8}$$

The functions of grinding process efficiency changes Eq(8), power inputs – Eq(6) and the duration – Eq(7) are shown in Figure 2.

The relation shown in Figure 2 presents that the grinding mode coefficient increasing from 0.75 to 0.861 allow to increase the grinding process efficiency up to 28.3 % and decrease the milling time down to 32.2 %, so that the power inputs for the grinding process are reduced down to 22 % while maintaining the marble granularity in a drum mill.

The experimental data of marble grinding are presented by the relations shown in Figures 3 and 4.

Figure 3 reveals the relation of the ground materials specific surface and the grinding mode coefficient at a different time of the grinding process.

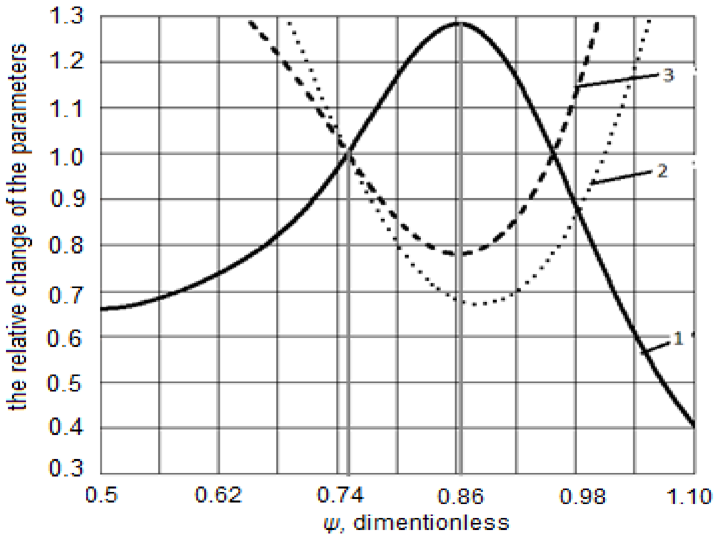

Figure 2: Changes of the dimensionless efficiency marble grinding process values (curve 1), milling time in minutes (curve 2) and the dimensionless power inputs (curve 3) in comparison with the process when the grinding mode coefficient value is 0.75

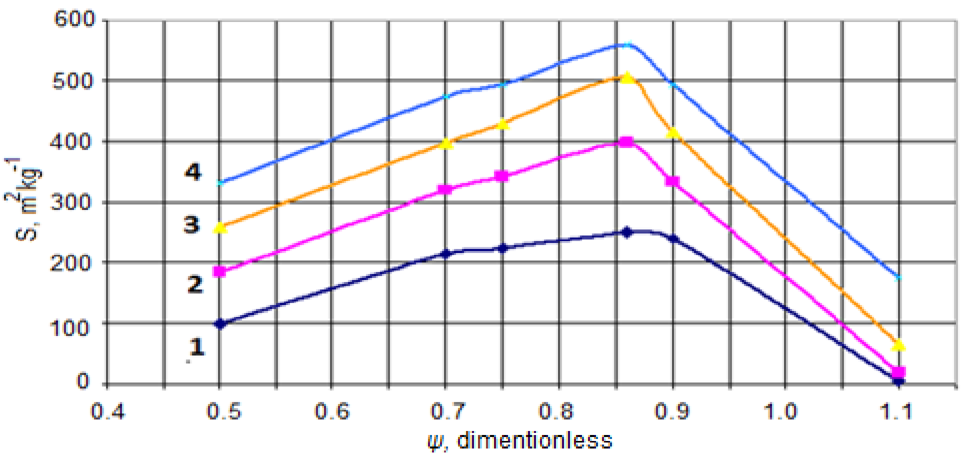

Figure 3: Relation of the marble specific surface (m^2 kg^{-1}) and the dimensionless grinding mode coefficient for various values of milling time: 1: 15 min; 2: 25 min; 3: 35 min; 4: 45 min

Figure 4 shows the kinetic relations of marble grinding for different values of the mode coefficients. These curves were obtained in studies of materials grinding processes in a ball mill. Velocity modes of the mill while grinding correspond to the grinding modes coefficient values 0.5, 0.7, 0.9, 1.1, 0.75, and that defined by the calculation of Eq(3), namely marble 0.861. Comparative evaluation of changes in power inputs and grinding time of each material was carried out on the data obtained on the basis of the experimental curves 1 and 2 shown on Figures (4). The curves marked with number 1 in Figure 4 correspond to the grinding mode coefficients defined by the suggested method for each material. The relation 2 built depending on the experimental data of the grinding processes, which are characterized by the mode coefficient 0.75. The fixation with a constant specific surface value for each material made possible to determine by the suppression of the constructed constant line with curves 1 and 2 the points corresponding to the time of the grinding process which are required for the data showing this specific surface area. Such a plotting not only allows to get the grinding process value, but also shows the advantage of the determined according to the suggested method ball mill operating modes implementation compared to the modes using commonly recommended coefficient value.

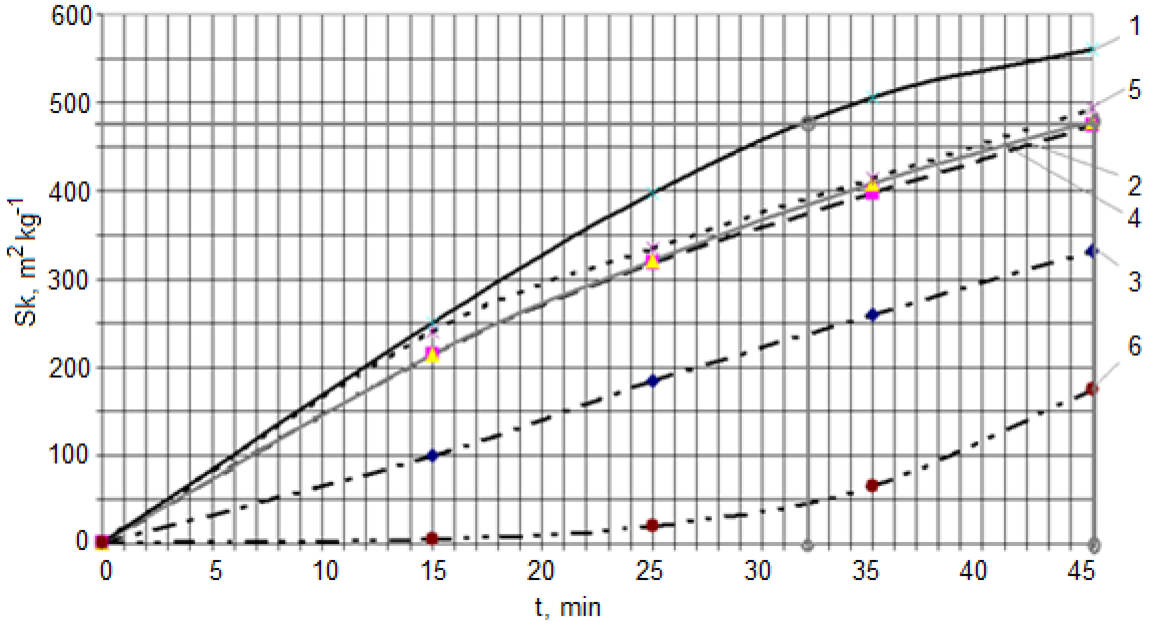

Figure 4: Relation of the marble specific surface (m^2 kg^{-1}) and grinding time (min) with different values of the dimensionless grinding mode coefficient: 1: ψ = 0.862; 2: ψ = 0.75; 3: ψ = 0.5; 4: ψ = 0.7; 5: ψ = 0.9; 6: ψ = 1.1

The experimentally obtained curves in Figure 4 suggest that the decrease in power inputs is 18.3%, and the decrease in milling time – 28.9%. Theoretical relations presented in Figure 2 show that increasing the grinding mode coefficient from 0.75 to 0.861 can increase the efficiency of the marble grinding process up to 28.3% and decrease the milling time down to 32.2%, so that the grinding process power inputs are reduced to 22% at maintaining the marble granularity in a drum mill. Theoretically, the data are adequate to the experimental ones. The energy-efficient modes use for grinding of materials with different physical and mechanical properties in ball mills causes significant power inputs savings in industrial processes of modern industry branches.

4. Conclusions

Theoretical, analytical and experimental research of grinding process in a ball mill showed, that there is a possibility of grinding power effectiveness increase by means of a direct blow, by providing: grinding mode and correlation of destructive loads during a definite material dispersion with given physical-mathematical characteristics. It was created a phenomenological model of hard materials grinding process power effectiveness in a ball mill and scientifically proved the theory of a grinding mode coefficient calculation, which corresponds with the coefficient of efficiency peak value of a definite material grinding process. It was created a comparative evaluation method of a calculated mode with traditionally recommended ones. The use of the introduced ball mill modes gave an opportunity to get time reduction of grinding: cement clinker – down to 28.9 %, black coal – down to 18.4 %, marble – down to 28.9 % and rock salt – down to 19.6 %. The decrease of power inputs made up 18.3 % for cement clinker, 9.4 % for black coal, 18.4 % for marble and 10.4 % for rock coal.

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