Analysis of power parameters of a rotary mill

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Abstract. The paper (publication) presents a description of the developed design of a rotary mill with a complex mechanical and acoustic effect on the dispersed material, as well as analytical studies of the parameters of energy consumption of a rotary mill, based on the main physical processes occurring in it. The research was carried out by mathematical and simulation modeling of technological processes in the grinding chamber of the mill, as well as on various technological paths of the unit. To determine the main parameters that make up the total power consumption of the unit, an approach was chosen to differentiate the processes by their physical nature and contribution to the formation of the total power consumption of the rotary mill.

The obtained results of mathematical modeling of processes occurring inside the technological paths of the unit allowed getting expressions for determining the main power costs of the unit depending on the characteristics of the unit design for each component of the total power required for effective operation of the unit at the required parameters of the dispersion of the finished product.

1. Introduction

In view of the need for materials with high specific surface characteristics, mechanical engineering is faced with the task of developing and calculating effective technological equipment that could successfully meet these requirements in the production of construction materials and products. In accordance with this, the team of engineers formulated a goal in the need to design and calculate a special shredder that would be able to combine in its design various effects on the crushed material and solve various technological problems, which would increase the efficiency of the process of dispersion and homogenization of dispersed systems, increase the specific surface area of the finished product and reduce the specific energy consumption in industrial production.

To achieve this goal, the design of a rotary mill [1] was proposed for complex mechanical and acoustic effects on the dispersed material. The essence of the design presented in figure 1 is expressed in the fact that at one of the technological stages of pre-dispersion, the principle of shock-shear strains
is used; at another stage of the main grinding, the principle of vortex and acoustic action with a reflective effect on the mill stator; at other stages, the vortex-acoustic effect is used (to avoid agglomeration of fine particles); as well as in the mill design, it is possible to carry out dispersible mixing of dissimilar materials [2].

Using the resulting three-dimensional model of the projected unit, they can predict the behavior of the material at any stage. We used the FloXpress application in the SolidWorks 2018 program to simulate various processes that occur in the unit.

Figure 1. Rotary mill of complex mechanical and acoustic action: 1 – loading components; 2 – transportation or pre-shredding; 3 – the stage of grinding under the action of shock-shear strains; 4 – grinding with the use of the impact effect; 5 – processing of air-material flow in disk headsets (partial deagglomeration of particles); 6 - pneumohomogenization of dispersed powders, or acoustic dispersion; 7 – discharging the finished product.

The design of the rotary mill under consideration includes the possibility of various mechanical effects on the dispersed material. The combination of successive (or simultaneous) types of mechanical effects on the dispersed material, such as impact, abrasion, sound effects of acoustic wave vibrations, reduces the consideration of the grinding process in the mill to a complex approach, and the combination of such effects has every right to be called complex [2].

The works of Kirpichev, Kik, Rittinger, Rebinder, Bond, and Rundkvist are the most widely used in all the existing variety of developed theories for calculating energy costs for grinding [4], however, there are studies by modern authors that have significantly improved and clarified the classical understanding of this process [5,6] with respect to specific types of grinders.

2. Materials and methods

Let us express the necessary complete work spent by rotary mill in the dispersion process, as the sum of certain works: friction work - \( W_f \); impact dispersion work - \( W_y \); work of mechanical and acoustic destruction of particles from the influence of resonators - \( W_a \). Then they can get an expression for the complete dispersion work, taking into account that the various stages of grinding the material in the mill will imply certain equations for the complete dispersion work:

\[
W_{comp} = \sum W = W_y + W_n + W_a.
\] (1)

The impact dispersion of material particles in a rotary mill is defined by a well-known expression:

\[
W_y = \frac{\sigma_t^2 \cdot V_q}{2E}.
\] (2)

where \( V_q \) – particle volume of the dispersed material, \( m^3 \);
\( \sigma_t^2 \) - the strength of the material particles (compression), \( Pa \);
\( E \) – modulus of longitudinal elasticity of the dispersed material, \( Pa \).

We assume that the shape of the particle is spherical [4].
Taking into account [7] the energy parameter $\xi$ plays an important role and indicates the ratio of the initial velocity of the particle before impact and the velocity of the particle after impact. This ratio is determined by the proportion of loss of movement speeds of the systems involved in the grinding process: the particle and the working body - the rotor:

$$\xi = \frac{v_0}{v_k},$$  \hspace{1cm} (3)

Here $v_0$ - initial particle velocity of the dispersed material, m/s;
$v_k$ - the final velocity of a particle of the dispersed material when it collides with the working element of the rotor, m/s.

We describe the value of the energy required for dispersion by the impact of a single particle of material at the first stage of the grinding process:

$$W_{y1} = \sum_{i=0}^{z_1} \frac{\xi_i^2 \cdot \sigma_i^2 \cdot V_i}{2E} = \sum_{i=0}^{z_1} \frac{\xi_i^2 \cdot \pi \cdot d^3}{12E} \equiv \sum_{i=0}^{z_1} \frac{0.25 \sigma_i^2 \cdot k \cdot d^3}{E},$$  \hspace{1cm} (4)

where $d$ - diameter size of the cross part of the particle, m;
$k$ - the formal particle coefficient of the dispersed material.

The expression for calculating strength is represented as:

$$\sigma_i = \sigma_u + \sigma_{\text{theoret.}} (1 - e^{-\beta i}),$$  \hspace{1cm} (5)

Here $\sigma_i$ - ultimate compressive strength during impact at the $i$-th stage of dispersion, Pa;
$\sigma_{\text{theoret.}}$ - theoretical value of the material compressive strength under impact, Pa;
$\beta$ - a scale coefficient that is determined empirically for each specific material;
$i$ - stage of dispersion.

We find the amount of energy at the second stage of dispersion, which is necessary for grinding a single particle of raw material from the initial size $d_{kp}$ to the specified one:

$$W_{y2} = \frac{0.25 k \cdot d_{kp}^3}{E} \sum_{i=0}^{z_2} \left[ \xi_i \left( \sigma_u + \sigma_{\text{theoret.}} (1 - e^{-\beta i}) \right) \right]^2,$$  \hspace{1cm} (6)

where $z_2$ - dispersion stage.

The theoretical value of the material strength in compression during impact we calculate using Orowan-Kelly equation [8]:

$$\sigma_{\text{theoret.}} = \sqrt{\frac{E \cdot S_{\text{theor.}}}{r_0}},$$  \hspace{1cm} (7)

where $S_{\text{theor.}}$ - surface energy of a solid on an area of 1 cm$^2$; $r_0$ - the interatomic distance in the equilibrium state, cm.

Let us represent the notation of possible normal stresses from the shock pulse $S$ as $\sigma_4$, from the influence of the back-up force $F_{\text{back}} - \sigma_3$.

Possible stresses $\sigma_4$ from the impact pulse $S$ of the mill rotor on a particle of the dispersed material can be calculated from the dispersion criterion:

$$|\sigma_4| \geq [\sigma]_c,$$  \hspace{1cm} (8)

where $[\sigma]_c$ - acceptable possible normal compression stresses of the dispersed material, Pa, which, in turn, can be set from the equation:

$$[\sigma]_c = \sigma_{\text{theoret.}}.$$  \hspace{1cm} (9)

Taking into account equations (8) and (9), it can be concluded that:

$$\sigma_4 = \sigma_{\text{theoret.}}.$$  \hspace{1cm} (10)

The stresses in the material also have a value associated with the impact pulse $S$, so it can be written as follows:

$$\sigma_4 = \frac{F_{\text{imp}}}{S_k},$$  \hspace{1cm} (11)
where $F_{imp}$ – impact force of the rotor on a particle of the dispersed material, N;
$S_k$ - contact area of the material particle with the rotor, m².

If we consider that in practice, for various geometric shapes of particles and their sizes, the pulse $S$ from the impact force $F_{imp}$ will be transmitted to the particle via an infinitesimal value of $S_k$, then:

$$\sigma_4 = \lim_{S_k \to 0} \frac{F_{imp}}{S_k} = \text{sign} \left( F_{imp} \right). \quad (12)$$

So expression (12) in expression (5) is represented as:

$$\sigma_i = \sigma_4 + \text{sign} \left( F_{imp} \right) \left( 1 - e^{-\beta_i} \right). \quad (13)$$

This expression (13) quantifies the boundary value of the compressive strength during the impact pulse $S$ at the $i$-th stage of dispersion, depending on the geometric dimensions of the mill working elements and their speed during the impact period.

It is known that the possible normal stresses from the compression of particles on impact contribute to the appearance of tangential stresses $\tau$ in the particle, which, according to Mohr’s theory of strength, are defined as:

$$\tau_{\text{max}} = \pm \frac{\sigma_{\text{theoret}}}{2}. \quad (14)$$

Taking into account the above and in accordance with the provisions of the Mohr strength theory, we make an assumption about shock-shear strains of particles during dispersion of the material. These strains contribute to the formation of new surfaces of the dispersed material, as well as to the production of powders with a lighter subsequent destruction of already thin particles at further stages of raw material grinding. Next, we get the expression (6) taking into account (13) in the form:

$$W_{y2} = \frac{0.25k \cdot d_{kp}^3 \cdot \sum_{i=0}^{z_2} \xi_i \left( \sigma_4 + \text{sign} \left( F_{imp} \right) \left( 1 - e^{-\beta_i} \right) \right)^2}{E}. \quad (15)$$

The grinding of material particles during dispersion and impact interaction in an infinitesimal period of time occurs under the action of friction forces.

Let us note that each stage of dispersion due to attrition increases the number of fine particles by a $(1 - \xi)$ times, while the total volume of material particles subjected to destruction is the following value - $k \cdot d_{kp}^3 \left( 1 - \xi^2 \right)$.

Based on the above, we will find the work of the friction forces spent on the abrasion of $(1 - \xi)$ part of the material for parts with the initial size $d$:

- for the first dispersion stage
  $$W_{n1} = \frac{0.25\sigma_{\text{theoret}}^2}{E} k \cdot d_{kp}^3 \left( 1 - \xi^2 \right), \quad (16)$$

- for the second dispersion stage:
  $$W_{n2} = \frac{0.25\sigma_{\text{theoret}}^2}{E} k \cdot d_{kp}^3 \left( 1 - \xi^2 \right), \quad (17)$$

We obtain the equation of the work required to disperse the material from the initial particle size $d$ to the critical- $d_{kp}$ in $z_1$ stages, in accordance with expressions (4) and (16):

$$W_{y1} + W_{n1} = \frac{0.25 \cdot k \cdot d_1^3}{E} \cdot \sum_{i=0}^{z_1} \xi_i + \sigma_{\text{theoret}}^2 \cdot \left( 1 - \xi^2 \right). \quad (18)$$

Then, in the same way, we add the components (15) and (17) for the material particles from the size of the beginning of the scale effect $d_{kp}$ to the final size $d_2$ at the $z_2$ stage:

$$W_{y2} + W_{n2} = \frac{0.25k \cdot d_{kp}^3}{E} \left( \sum_{i=0}^{z_2} \xi_i \left( \sigma_4 + \text{sign} \left( F_{imp} \right) \left( 1 - e^{-\beta_i} \right) \right)^2 \right) + \sigma_{\text{theoret}}^2 \cdot \left( 1 - \xi^2 \right). \quad (19)$$
To find the results of mathematical modeling, we obtained an expression for the dispersion of a material with a mass of \( M \). We multiply the expression by the number of particles \( N \) contained in the material with a mass \( M \):

\[
W_y + W_n = \frac{M}{N} \left( \sigma_i^2 \sum_{i=0}^{z} \xi_i + \sigma_{\text{theoret}}^2 (1 - \xi^{z+1}) \right) + \frac{2^{z+1} d_{\text{co}}^3}{d^3} \sum_{i=0}^{z} \left[ \xi_i \left( \sigma_i + \text{sign} \left( F_{\text{imp}} \right) \left(1 - e^{-\beta_i} \right) \right)^2 + \sigma_{\text{theoret}}^2 \left(1 - \xi^{z+2} \right) \right],
\]

(20)

where \( \rho \) - particle density of the dispersed material, kg/m\(^3\).

If with each subsequent stage the particle is destroyed into several \( c \) - parts, we get:

\[
c^z = \frac{d^3}{d_{\text{co}}^3} = i^3.
\]

(21)

As it was assumed above \( c = 3 \), we will determine the number of stages for a certain size of the fraction of the dispersed material:

\[
z = \frac{3 \lg i_i}{\lg 2} \approx 10 \lg \frac{d}{d_x}.
\]

(22)

Based on (20), (21), (22) we conclude that the work that must be spent on dispersing the mass of the material with a volume of \( M \) under complex mechanical action from the initial to the final particle sizes is determined by the equation of the form:

\[
W_y + W_n = \frac{M}{N} \left( \sigma_i^2 \sum_{i=0}^{10 \lg d_{\text{co}}} \xi_i + \sigma_{\text{theoret}}^2 \left(1 - \xi^{10 \lg d_{\text{co}}} \right) \right) + \frac{2^{10 \lg d_{\text{co}}} \rho_{\text{co}}^3}{d^3} \sum_{i=0}^{10 \lg d_{\text{co}}} \left[ \xi_i \left( \sigma_i + \text{sign} \left( F_{\text{imp}} \right) \left(1 - e^{-\beta_i} \right) \right)^2 + \sigma_{\text{theoret}}^2 \left(1 - \xi^{10 \lg d_{\text{co}}} \right) \right],
\]

(23)

In order to calculate the component equation (1) related to the work of destruction of dispersed particles under the influence of acoustic waves of resonators - \( W_a \), we use the equation:

\[
W_a = P_{\text{ak}} \cdot V_x^3,
\]

(24)

where \( P_{\text{ak}} \) - acoustic pressure in an elastic medium, Pa;

\( V_x^3 \) - volume of the particle affected by acoustic pressure, m\(^3\).

The value of variable acoustic pressure can be determined by the amplitude of particle vibrations in the air by the formula:

\[
P_{\text{ak}} = 2 \pi \cdot \omega \cdot \rho_{\text{ac}} \cdot C \cdot A_a,
\]

(25)

here \( \omega \) - frequency of oscillation of the wave at which the particle is destroyed, Hz;

\( \rho_{\text{ac}} \) - two-phase flow density, kg/m\(^3\);

\( C \) - the speed of ultrasound distribution, m/s;

\( A_a \) - oscillation amplitude of dispersed particles, m.

Based on the above expressions included in equation (1), we finally get:
3. Results and summary

As a result of research on the design of a rotary mill using computer programs and mathematical modeling: analytical expressions are obtained to determine the main parameters of energy consumption of a rotary mill, based on the main physical processes occurring in it and its structural and technological features. As a result, it was found that the diameter of the final product particles exceeding the critical particle size is guaranteed by a more rational process of combined effect of impact with abrasion in combination with mechanical and acoustic impact. The obtained results of mathematical modeling of processes occurring inside the technological paths of the unit allowed obtaining expressions for determining the main power parameters.

4. References

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