Optimization of material grinding in vibration mills

V S Bogdanov, E B Alexandrova, D V Bogdanov, N E Bogdanov and A Y Gavrunov
Belgorod State Technological University named after V. G. Shukhov, 46 Kostyukov Str., Belgorod, 308012, Russia

E-mail: v.bogdanov1947@gmail.com, aleksandrova76@mail.ru

Abstract. In many industries millions of tons of various materials are subjected to fine grinding. It is relevant to improve the quality of final products at minimum power consumption. Vibration mills are widely used to obtain powders with the particle size of the final product of less than 10 microns. Depending on the design of a drive from and the nature of vibrations of a grinding chamber they are divided into mills with harmonic, biharmonic and polyharmonic vibrations. The general disadvantage of such mills is stagnant zones in loading reaching 30% of the grinding body weight. Thus, the efficiency of grinding is reduced. The paper considers a new design of a rotary vibration mill without stagnant zones, which significantly increases productivity and grinding fineness of the final product. It describes the equations that were obtained to calculate the power consumption of a drive and the kinetics of grinding.

1. Introduction.
Vibration mills with different design are widely used to obtain powders of less than 5 microns in size [1]. Vibration mills with eccentric weight, which rotation axis passes through the center of gravity of vibrating masses (grinding bodies and mill feed) gained their widest distribution. The case of such mills makes harmonic vibrations. The grinding bodies move under the influence of friction forces in direction opposite the rotation of eccentric weight and at the same time rotate around their own center of gravity.

The disadvantage of vibration mills with harmonic vibrations is the fact that up to 30% of grinding bodies in the central part of loading constitute stagnant zones and do not take active part in the grinding process. Besides, there is the segregation of grinding bodies and the mill feed – large grinding bodies are moved to the top of loading, while the small one – down, i.e. they are divided by fineness. This significantly reduces the efficiency of grinding.

In recent years mills with biharmonic and polyharmonic vibrations of a mill body are ver more widely used [2–7].

The distinctive feature of such mills is the fact that the rotation axis of the eccentric weight is displaced in relation to the axis passing through the center of gravity of the mill body and the eccentric weights are placed beyond the boundaries of the mill body [2, 3]. However, the design of such mills is quite complicated, which reduces their operating reliability.

The design of mills when vibrators are located in mutually perpendicular planes is particularly interesting [4, 5]. The trajectory of movement of the grinding bodies is characterized by the Lissajous figures, which form depends on weight, frequency and direction of rotation of eccentric weights.

The most perspective area of application of vibration mills is the preparation of multicomponent construction mixes, which include 5÷8 various components with quite different size of particles and volume weight [8].
This ensures not only grinding, but also highly efficient homogenization of multicomponent mix, which significantly increases its quality and consumer properties.

2. Materials and methods

For the first time in the Russian Federation we proposed a new design of rotary vibration mills [9], which kinematic scheme is shown in Figure 1.

The mill turns on the cylindrical grinding chamber 1, the geometrical axis 7 of a mill shell 1 is located at angle \( \alpha \) to the rotation axis of a feed shaft 3. Material and grinding bodies are loaded into the grinding chamber via a hatch 6. The mill is fixed on springs 2. A vibrator 4 is installed on a mill body. The grinding chamber 1 rotates from electric motor 5 connected to shaft 3 via elastic coupling.

![Figure 1. Kinematic scheme of a rotary vibration mill: 1 – grinding chamber; 2 – spring support; 3 – feed shaft; 4 – vibrator; 5 – drive; 6 – loading (unloading) hatch; 7 – mill shell axis.](image)

The mill operates as follows. The grinding bodies and the mill feed in the amount of 80-85\% of the volume of the grinding chamber are placed via hatch 6 into the grinding chamber 1. Vibrator 4 and electric drive 5 turn on simultaneously. Due to the inclination of axis 7 of the grinding chamber the grinding bodies make complex spatial motion not only in cross section of a mill shell, but also reciprocal motion along axis 7 of a mill shell and vibration harmonic vibrations. At the same time all stagnant zones in loading are destroyed, the movement of grinding bodies is intensified, their segregation is prevented, material grinding process is intensified.

The rotary vibration mill with inclined mill shell creates grinding conditions for almost all grinding bodies, which increases the efficiency of grinding in general.

The rotation frequency of a mill shell shall ensure that all stagnant zones are destroyed and at the same time the efficiency of vibration grinding is not decreased. It was experimentally proved that the rotation frequency of a mill shell is 0.2 from the critical one. At such rotation frequency of a mill shell the grinding bodies move in the cascade mode thus making cross-longitudinal circulating movements towards a mill shell and grind the material via intense attrition.

We conducted pilot studies of a rotary vibration mill to define the rational modes of grinding.

3. Experimental studies

The work for movement of grinding bodies in vibration and cascade modes is defined by the following equation:

\[
A = 2\pi \varphi a b g \rho L \left( \left( \frac{Y_a}{\cos \alpha} - Y_R \right) R + f_{TP} (1 - 2Z_n) L \right),
\]
where $\phi$ – mill shell load factor; $a$, $b$ – face bottom parameters (width, height); $\rho$ – bulk density of loading; $f_{fr}$ – coefficient of rolling friction of loading on internal surface of a mill shell; $L$ – mill shell length; $\alpha$ – mill shell tilt angle; $Y_d$, $Y_{R}$, $Z_R$ – coordinate of the center of gravity.

The most critical factors were chosen for the study: load factor of a grinding chamber with grinding bodies – $\phi_1$; charge coefficient of grinding material – $\phi_2$; rotation frequency of a grinding chamber – $n$ and the vibration frequency of a grinding chamber – $\omega$.

The following were chosen as the optimization parameters most fully characterizing the grinding process: productivity of a mill – $Q$ (kg/h); specific power consumption – $q$ (kW∙h/kg); specific surface of a final product – $S$ (m²/kg) [10].

Experiments were conducted on the basis of a full factorial experiment within the central composite orthogonal design (CCOD) $2^4$.

The following regression equations in the natural form were obtained through experiments:

$$Q = 39.7 + 14.9\phi_1 - 0.67n - 2.18\omega + 145.7\phi_2 - 30\phi_1^2 + 11.9\phi_2^2 + 0.64\omega\phi_1 - 22.5\phi_1\phi_2;$$

$$q = 0.39 - 0.46\phi_1 - 1.07\phi_2 - 0.004n - 0.002\omega + 0.3\phi_1^2 - 0.25\phi_2^2 - 0.02\phi_1\phi_2 + 0.02\omega\phi_2;$$

$$S = 484.6 - 5.0\phi_1 + 6.2n - 15.8\omega - 370.0\phi_2 - 280\phi_1 + 6250.0\phi_2^2 - 250.0\phi_1\phi_2 - 48.8n\phi_2 - 28.0\omega\phi_2$$

(4)

The study revealed that the weight of grinding bodies ($\phi_1$) and the weight of a mill feed ($\phi_2$) have the greatest impact on mill productivity $Q$. This conclusion corresponds to the physics of grinding – the more the grinding bodies and the mill feed, the higher the mill productivity. The effect of influence of the weight of a mill feed ($\phi_2$) is 9.7 times higher than that of the weight of grinding bodies ($\phi_1$). The influence of vibration frequency of a mill body on its productivity is 3.3 times higher than the rotation frequency of a mill shell. It shall be noted that out of cross-coupling effects the effect $\phi_1\phi_2$, i.e. the load weight has the greatest impact on productivity.

The quality of the final product is estimated by its specific surface – $S$. The analysis of the regression equation (4) makes it possible to draw the following conclusions.

In this case the factor $\phi_2$ – amount of mill feed also has a determining influence on the specific surface of the final product. The more $\phi_2$ material in a mill, the less specific surface of the final product, i.e. the coarser the grinding.

For example, at $\phi_2 = 0.1$ the specific surface $S$ of the final product makes 310 m²/kg, productivity – 6.5 kg/h, specific power consumption – 0.05 kW·h/kg. With the increase in the amount of a mill feed up to $\phi_2 = 0.2$ the specific surface of the final product is reduced to 200 m²/kg, at the same time the specific power consumption makes 0.05 kW·h/kg and productivity – 2kg/h.

The vibration frequency has over 3 times bigger influence than the rotation frequency of a mill shell. At constant vibration frequency of 50 Hz and the rotation frequency of a mill shell of 12 rpm the specific surface of the final product with the productivity of 5 kg/h made 200 m²/kg, specific power consumption – 0.052 kW·h/kg. With the increase of rotation frequency of a mill shell up to 24 rpm the specific surface of the final product increases up to 295 m²/kg, i.e. by 47%, productivity – 9.5 kg/h, specific power consumption – 0.03 kW·h/kg.

The loading weight has the biggest impact on specific power consumption of $q$ (3), while the rotation frequency $n$ of a mill shell and vibration frequency $\omega$ have the smallest impact.

The rational mode of the grinding process was established during pilot studies, which ensures the following: maximum capacity, maximum specific surface of the final product, minimum power consumption. The load factor by grinding bodies makes $\phi_1 = 0.6-0.7$; load factor with mill feed $\phi_2 = 0.12-0.8$; rotation frequency of a mill shell $n = 22-23.7$ rpm; vibration frequency of the grinding chamber $\omega = 52-57$ Hz.

During experiments the quartz sand used as one of the components in dry construction mixes was subjected to grinding. The particle-size analysis of received samples at specific surface of the final
powder of 350 m²/kg showed that the samples contain 90% of particles with the size of 80 microns, 70% – 40 microns, 50% – 23 microns and 20% – less than 5 microns.

4. Theoretical background of energy parameters

The total capacity of a mill drive includes capacity \( N_1 \) for the rotation of a mill shell and capacity \( N_2 \) for vibration.

\[
N_1 = A n, \tag{5}
\]

where \( A \) – work on the movement of grinding bodies (1); \( n \) – rotation frequency of a mill shell.

\[
N_2 = 0.5(1 - K_0)m_1\omega^2\alpha_1\alpha_2[\sin(\alpha_1 – \alpha_2)], \tag{6}
\]

where \( K_0 \) – coefficient considering accession of a part of the grinding bodies to the mass of mobile parts of a mill; \( m_1 \) – loading weight; \( \omega \) – rotation frequency of eccentric weight shaft; \( \alpha_1, \alpha_2 \) – amplitude of vibrations of grinding bodies and a mill body, respectively; \( \alpha_1, \alpha_2 \) – vibration phases of grinding bodies and mill feed.

Such physical-mechanical properties of a material as strength, hardness, fragility have significant effect on material grindability. In a rotary vibration mill the grinding of a material is performed by intense attrition, and one of the parameters characterizing the quality of the final product is its specific surface [11].

For a rotary vibration mill we received the equation of grinding kinetics to calculate the specific surface of the final product:

\[
S = S_1 - (S_1 - S_0)\exp \left(\frac{S_0K_N}{S_1 - S_0}t\right), \tag{7}
\]

where \( S_1 \) – limit value of specific surface which can be obtained in a rotary vibration mill; \( S_0 \) – initial specific surface of mill feed; \( K \) – grindability index; \( N \) – total capacity of a mill [12]; \( t \) – grinding time.

5. Conclusion

Thus, the comprehensive analysis of existing designs of vibration mills made it possible to develop a rotary vibration mill with inclined mill shell. Rational parameters of the grinding process were experimentally defined. The equations to calculate power consumption of a drive and the kinetics of the grinding process were received.

Acknowledgments

The work is performed in the framework of the Flagship University Development Program at Belgorod State Technological University named after V.G. Shukhov, using the equipment of High Technology Center at BSTU named after V.G. Shukhov.

References

[1] Andres K and Haude F 2010 Application of the PallaTM vibrating mill in ultra fine grinding circuits The J. of the Southern African Institute of Mining and Metallurgy 110 125-13
[2] German Patent DE322117 A 1 B02C19/16 Schwingmühle (29 December 1983)
[3] US Patent No. 4164328 B02C 17/14 Vibratory ball or tube mill (14 August 1979)
[4] Kwon J, Lee H and Cho H 2008 3D discrete element method simulation to various types of mill Geosystems Engineering (Seoul National University) 11(1) 19-24
[5] Xiaohong J and Yongzhong Z 2010 Vibrating mill grinding media group simulation Mechanic Automation and Control Engineering (MACE), Int. Conf. on 26-28 June 2010 (Wuhan) pp 2335-2338
[6] Beenken W, Gock E and Kurrer K 1996 The outer mechanics of the eccentric vibration mill Mineral Processing 44-45
[7] Gock E, Florescu R and Betgovargez W Process of the preparation of fibrous materials in an eccentric vibratory mill Europatent No. 0672469A1; B09B3/00; C04B20/02 (20 September 1995)
[8] Gerasimov M D, Brazhnik Y V, Gorshkov P S and Latyshev S S 2018 Processing Equipment, Mechanical Engineering Processes and Metals Treatment 11 042022
[9] Artyomenko K I and Bogdanov N E, RU Patent 2637215 C 1, B02C19/16 Vibration mill (1 December 2017) Bulletin No. 34
[10] Gavrunov A Yu, Bogdanov V S and Fadin Yu M 2015 Rotary vibration mill with longitudinally cross movement of grinding bodies (Belgorod: BSTU)
[11] Eltsov M Yu, Bogdanov V S, Bogdanov N E, Alexandrova E B, Gavrunov A Yu and Karagodina K I 2017 Bulletin of BSTU named after V.G. Shukhov 4 101-109
[12] Kano J, Mio H and Saito F 2000 Correlation of grinding rate of gibbsite with impact energy of balls AIChE Journal 46(8) 1694-1697