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THE PROCESS OF THE MILL FEED FLOW ALONG A CURVED ACTING FACE OF A VIBRATION MILL SCREEN

The article describes the studies into the process of the mill feed flow along a curved vibratory surface under the action of oriented vibrations. The differential equation of the relative movement of a grinding body in a layer of a milled material along the surface are given. The differential equation of a particle motion is obtained. The equations prove that at a certain ratio of the vibration parameters, the grinding balls of different sizes when moving upward in a milled mass have limit heights. It is found that the best size distribution of the grinding balls on the vibratory surface exists at a certain ratio of the vibration amplitude and frequency and the tangent slope of the acting face. The plotted experimental curves prove that the maximum efficiency of the process is achieved at the acting face vibration amplitude in a range of 0.6–0.8 mm and vibration frequency in a range of 48–54 Hz, and is 8–12% higher than at the amplitudes and frequencies beyond these ranges.

Keywords: *fine milling, mill screen, curved vibratory surface, mill feed, different size balls, vibration amplitude, vibration frequency*
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Introduction

The current designs of the milling equipment fail to enable fine milling and simultaneous sizing of mineral raw material at minimum energy inputs. The reason of that is the impossibility of oriented effects to be exerted by grinding bodies on different size particles of a material being milled [1–7].

The authors propose a new method of milling and a new design of a vibration mill screen with oriented vibrations of a curved acting face. As a result, the grinding balls of different diameters exert the oriented effects on the particles being milled [8–11].

The curved acting faces have proved to be effective separating tools in various mining and processing processes. Such faces are simple and reliable in manufacture and operation. Such faces are for instance the AURY curved vibrating screens operated in separation of magnetite from products of processing and desliming [12, 13]. However, there is yet no information about using these screens in simultaneous milling and sizing.

The key objective of this research is the mechanics of movement of a mill feed represented by balls of different diameters and to-be-milled particles of different sizes bottom up a curved acting face because of effect of oriented vibrations. The scope of the research also encompasses determination of such ratio of the design variables and operating conditions of a vibration mill screen that large grinding bodies mill large particles at the bottom of the grinding chamber and small grinding bodies treat small particles at the top of the grinding chamber. In this case, the milling process includes size grading of both the grinding bodies (balls) and ground material. To this effect, it is required to ensure displacement of the balls from the bottom of the grinding chamber together with the mill material to various heights upward the curved acting face. As a result, it is possible to improve the milling quality and to eliminate the nonproductive loss of energy in interaction of balls and particles of different sizes. One more task of the research is the experimental optimization of operating conditions of the vibration mill screen.

Research methods and materials

The study of the dynamics of a grinding body in a material layer examines displacement of a ball upward a material layer over a curved surface. The slopes of the tangents to the surface change as it goes up, from 0° to a vibration angle β along the whole surface length selected from a condition that balls lie on the surface in single layer (**Fig. 1**). A ball with a diameter d and a mass m, in the layer of a material on the curved acting face of a vibrating machine, experiences the gravity force F_g, the friction force F_f, the normal force F_n and the inertia force F_i.

The differential equations of movement of a grinding body relative the axes x, y in a layer of a material as a function of the time t along a curved acting face are given by:

$$\left.\begin{aligned} m\ddot{x} &= -mg\delta\sin\alpha + mA\omega^2\sin\omega t\sin\beta - F_f, \\ m\ddot{y} &= -mg\delta\cos\alpha + mA\omega^2\sin\omega t\cos\beta + F_n \end{aligned}\right\}, \qquad (1)$$

where β is the vibration angle; A and ω are, respectively, the amplitude and frequency of the acting face vibrations; m is the mass of a grinding body; g is the acceleration of gravity; δ is the movement resistance of the ball, dependent on the size and shape of the particles, and on their

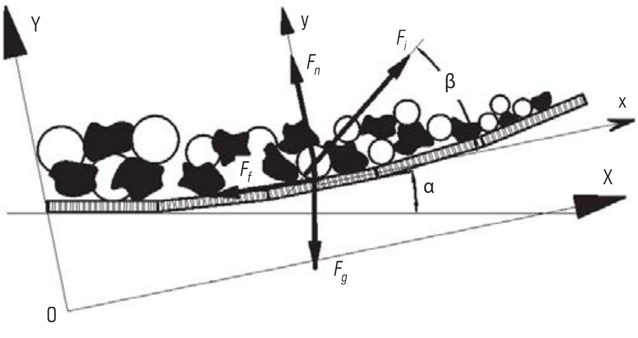

Fig. 1. Grinding body (ball) in material layer on curved surface which carries out oriented harmonic vibrations

mechanical properties; α is the slope of the curved acting face tangents to horizon at the point of contact with the ball.

Assuming the ball to move under the action of the oriented vibrations in the mass of the mill feed along the vibrating surface in the no-detachment mode, and considering that $F_f = fF_n$, where f is the friction factor as an averaged indicator of properties of the mill mix between the ball and the acting face, the normal force F_n applied by the acting face on the milled body is written as follows:

$$F_n = \frac{mg\delta}{\sqrt{1+\dot{x}^2}} - mA\omega^2 \sin\omega t \left(\frac{\cos\beta}{\sqrt{1+\dot{x}^2}} - \frac{\sin\beta \dot{x}^2}{\sqrt{1+\dot{x}^2}} \right). \quad (2)$$

After some trigonometric transformations, the differential equation of movement of a particle in the layer of a material is written as:

$$\ddot{x} = -\frac{g\delta\dot{x}^2}{\sqrt{1+\dot{x}^2}} + A\omega^2 \sin\omega t \left(\frac{\sin\beta}{\sqrt{1+\dot{x}^2}} + \frac{\cos\beta \dot{x}^2}{\sqrt{1+\dot{x}^2}} - \right.$$

$$\left. - f\left(\frac{g\delta}{\sqrt{1+\dot{x}^2}} + A\omega^2 \sin\omega t \right) \left(\frac{\cos\beta}{\sqrt{1+\dot{x}^2}} + \frac{\sin\beta \dot{x}^2}{\sqrt{1+\dot{x}^2}} \right) \right). \quad (3)$$

The analysis of this differential equation shows that the height of the different size balls going up the curved surface under the action of the oriented vibrations depends on the maximal acting face acceleration magnitude $A\omega^2$, the curved screen tangent slope α, the vibration angle β and the ball movement resistance δ [14–16].

Figure 2 describes the height of the grinding balls of various size in a mill material layer as function of the angle of the acting face. The studies included different friction factors between the material and the acting face at the selected parameters of the face vibration. The friction factors in Fig. 2 are borrowed from the Table of Friction Factors for Nonuniform Materials (Context Help GEO5).

It follows from the curves that at a certain height, a ball goes to a new quasi-equilibrium state, and that the different diameter and mass balls have different limit heights on the curved acting face of the screen.

In the steady-state operation of the vibration screen, the balls collide with the particles of the similar sizes while remaining at the achieved height. As a result, the process of milling takes no extra energy.

The curves of the upward velocity of the mill feed on the curved screening surface versus the amplitude of vibration at different vibration angles β show that the increase in the amplitude in the general case leads to the increase in the mill feed velocity. At the small (under 25°) and large (to 50°) angles β, a noticeable increase in the velocity of the balls is only observed at the amplitudes higher than 0.75 mm; at β = 37.5° the ball velocity markedly increases already at the amplitude of 0.5–0.7 mm. The literature recommends the vibration amplitudes to be not more than 0.5–0.8 mm for the vibration transportation [15]; thus, to stimulate the movement velocity and distribution of the balls on the acting face, β should range as 35–40° [17–20].

Figure 3 depicts the movement velocity v of the mill feed as function of the acting face vibration frequency ω for the grinding balls of different diameters at the vibration amplitude $A = 0.7$ mm and vibration angle β = 37.5°.

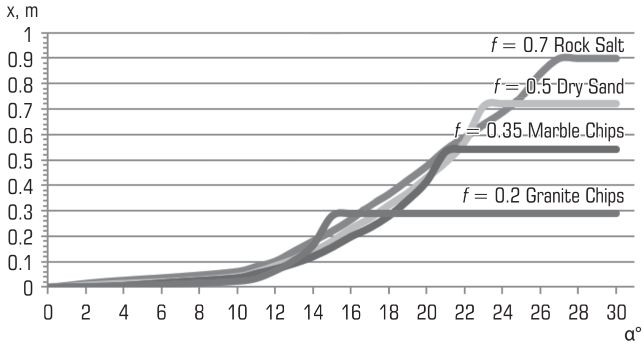

Fig. 2. Travel length x of grinding ball material layer versus curved acting face tangent slope α and friction factor f at constant A, β, ω

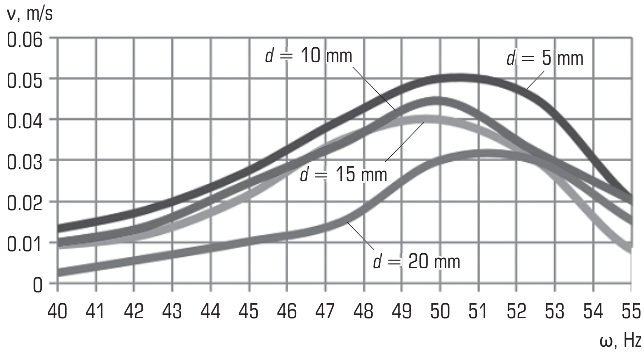

Fig. 3. Movement velocity v of grinding balls on curved acting face versus vibration frequency ω of curved acting face for different diameter balls at constant β and A

Results

The analysis of the obtained relationships shows that in the range of frequencies from 49 to 51 Hz, the rate of the vibro-distribution of the mill feed reaches maximum values. At the increasing frequency over 51 Hz, the velocity of the balls of different diameters lowers. Apparently, this is connected with the reduction in the total density (adhesion) of the balls and particles.

From the research evidence, it follows that the most efficient distribution of the mill balls in the layer of a material being milled on the curved surface requires that the curved acting face abides the following ranges of the process parameters: vibration angle β = 35–40°; vibration frequency ω = 49–51 Hz; vibration amplitude $A = 0.6$–0.8 mm.

The checkout of the theoretical relationships was carried out on a bench tester (**Fig. 4**).

The material to be milled was rock salt to 10 mm in size. During the tests, the varied parameters were the vibration amplitude and frequency of the acting face; the set of the grinding bodies; the size of the mill feed. The acting face of the bench tester was the curved perforated metal sheet. The shape of the curve was conditioned by the requirement of single-layer arrangement of different size balls on the acting face.

The response function was selected to be the milling–screening efficiency E, % [21] calculated from the outcome of the milling and further screening of a preset material sample through the holes on the acting surface within a preset time.

For the test data reliability estimation, the theoretical and experimental dependences of E on the vibrating machine parameters of the acting face vibration amplitude A and frequency ω were compared (**Fig. 5**).

The experimental curves plotted from the test data demonstrate that the maximal efficiency of milling is achieved at the vibrating face

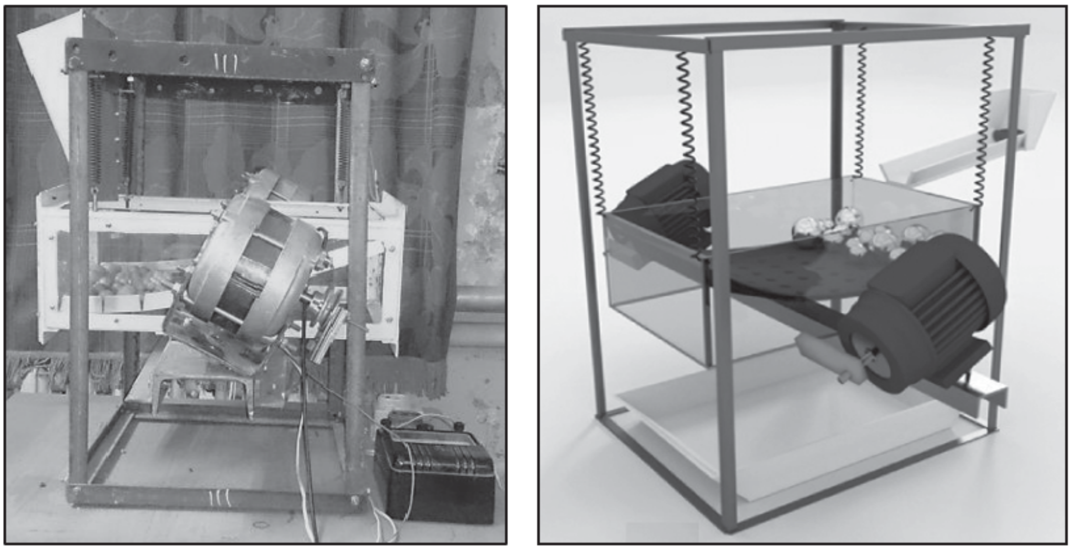

Fig. 4. Mill screen bench tester:
a–physical configuration;
b–3D model

amplitude in the range of 0.6–0.8 mm and frequency in the range of 48–54 Hz, and is 8–12% higher than at the values beyond these ranges of amplitudes and frequencies. This proves the theoretical results.

Conclusions

1. One of the promising machines for the fine mineral milling is the vibration mill equipped with an acting face capable of oriented vibrations which ensure the oriented effect to be exerted by the grinding balls of different sizes on the mineral particles to be milled. Moreover, this machine is simple and reliable.

2. The travel velocity of the grinding bodies (balls) of different diameters in the layer of particles on the curved surface depends on the surface vibration frequency ω and reaches maximum values in the frequency range from 49 to 51 Hz.

3. The height of the different size balls on the curved surface under the oriented vibrations depends on the maximum acting face acceleration magnitude $A\omega^2$, the acting face slope α, the vibration angle β and the ball movement resistance δ.

4. For the distribution of the grinding balls in the milled material layer on the curved acting face to be most effective, it is required to abide to the following ranges of the process variables of the acting face: vibration angle $\beta = 35–40°$; vibration frequency $\omega = 49–51$ Hz; vibration amplitude $A = 0.6–0.8$ mm.

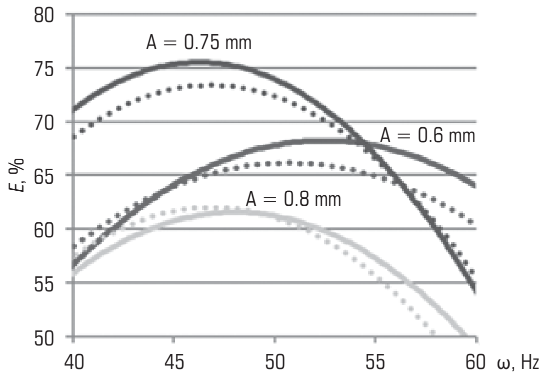

Fig. 5. Theoretical (solid) and experimental (dashed) curves of milling-and-screening efficiency and vibrating machine parameters

References

1. Akunov V. I., Litvinov G. P. General technical and economic indicators of counterflow jet mills. *Tr. Gos. Nauchno-Issled. Inst. Tsem. Prom.* 1982. No. 70. pp. 3–10.
2. Bardovskii A. D., Gerasimova A. A., Keropyan A. M. et al. Influence of the mechanical characteristics of harp screen material on screening process. *Proceedings of Higher Educational Institutions. Ferrous Metallurgy* 2018. Vol. 61, No. 9. pp. 678–682.
3. Snitko S. A., Yakovchenko A. V. Influence of the Axial Reduction Conditions on the Variation in the Thickness of a Wheel Rim at the Initial Stage of Rolling. *Metallurgist.* 2017. Vol. 61. pp. 387–393.
4. Hodakov G. S. High milling of construction materials. Moscow : Izdatelstvo literatury po stroitelstvu, 1972. 239 p.
5. Zhang X., Baia S., Jin W., Shi Z., Yu M. et al. Simulation research on vibration separation screen of air suction jujube picking machine based on Adams. *International Agricultural Engineering Journal.* 2020. Vol. 29, No. 2. pp. 128–134.
6. Bardovsky A. D., Valeeva L. M., Basyrov I. I. A plant with a rotary jet grinder to produce small fractions of mineral raw material. *IOP Conf. Series Materials Science and Engineering.* 2020. Vol. 971. DOI:10.1088/1757-899X/971/5/052004
7. Bardovsky A. D., Bibikov P. Ya., Deniskina T. V. Patent RF, No. 98340 Useful Model of Vibration Mill. Published: 20.10.2010.
8. Deniskina T. V. Theoretical study of the motion of grinding bodies and crushed material on a vibrating curved surface. *GIAB*. 2010. No. 12. pp. 203–205.
9. Astashev V. K., Pichugin K. A., Semenova E. B. Nonlinear dynamics of a vibrating machine with an electrodynamic actuator. *Journal of Machinery Manufacture and Reliability.* 2021. Vol. 50, No. 1. pp. 11–18.
10. Stepanenko A. I., Stepanenko A. A., Milshin O. N., Ordon S. F., Panov A. V. et al. Processing of low-grade bauxites by air separation. *Nonferrous Metals and Minerals : X International Congress Proceedings*. Krasnoyarsk : Nauchno-innovatsionnyi tsentr, 2018. pp. 48–54.

11. Gorbatyuk S. M., Zarapin A. Y., Chichenev N. A. Retrofit of vibrating screen of Catoca Mining Company (Angola). *GIAB*. 2018. No. 1. pp. 143–149.
12. Gnezdilov A. A. Implementation of resonant modes of technological vibrational machines. *Bulletin of Altai State Agricultural University*. 2019. No. 1(171). pp. 159–163.
13. Rumiche F., Noriega A., Lean P. et al. Metallurgical failure analysis of a welded drive beam of a vibrating screen. *Engineering Failure Analysis*. 2020. Vol. 118. 104936.
14. Chen Z., Tong X., Li Z. Numerical investigation on the sieving performance of elliptical vibrating screen. *Processes*. 2020. Vol. 8(9). 1151.
15. Blekhman I. I. Vibration Mechanics and Vibration Rheology (Theory and Applications). Moscow : Fizmatlit, 2018. 752 p.
16. Barbosa V. P., Menezes A. L., Gedraite R. et al. Vibration screening: A detailed study using image analysis techniques to characterize the bed behavior in solid–liquid separation. *Minerals Engineering*. 2020. Vol. 154. 106383.
17. Kobelev O., Valeeva L., Gerasimova A. Forging process flow development for plate production. *Solid State Phenomena*. 2021. Vol. 316. pp. 240–245.
18. Lahib M. E., Tekli J., Issa Y. B. Evaluating Fitts' law on vibrating touchscreen to improve visual data accessibility for blind users. *International Journal of Human Computer Studies*. 2018. Vol. 112. pp. 16–27.
19. John Kobbina A., Emmanuel Asuming F., Joe Oteng A. Optimization Algorithms for Solving Combined Economic Emission Dispatch: A Review. *Proceedings of the World Congress on Engineering and Computer Science*. 2019. pp. 210–215.
20. Altshul G. M., Guskov A. M., Panovko G. Ya. Dynamics of a resonant vibrator with an equal-frequency suspension of the working body and an unbalanced vibration exciter. *Obogashchenie Rud*. 2022. No. 1. pp. 51–55.
21. Deniskina T. V. Influence of the shape and angle of the vibrating surface of the working body vibration mill on the quality of the finished product. *GIAB*. 2015. No. 8. pp. 368–372. EM

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MODELING HEATING OF FAULTY ROLLER OF BELT CONVEYOR IN THE PRESENCE OF COAL DUST

Belt conveyor is a common means of transport in underground mines. At the same time, longwalls equipped with belt conveyors face high fire risk. One of the fire causes on belt conveyors is the seizure of rollers and their friction on the loaded belt in the long flight regions. The modern detectors of fire on belt conveyors fail to ensure ultra early sensing of inflammation. This article describes modeling of heating of a faulty roller in friction with a moving conveyor belt with a layer of coal dust. The modeling has found the rate of heating of the belt conveyor roller up to the temperature of the ultra early fire development with inflammation of coal dust particles, and the degree of effect of the coal dust layer on the fire onset speed. The graphic chart is plotted for the heat balance of a belt conveyor roller in friction-induced heating.

Keywords: *coal mine, ore mine, belt conveyor, roller, conveyor belt, exogenous fire, ultra early fire stage, fire initiation signs, heat transfer*
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Introduction

Belts are the common conveying equipment in mines. The high conveying capacity, long haulage and relatively simply maintenance makes this equipment highly popular in underground mining [1].

Alongside with the apparent advantages, the operation of conveyor belts includes complex fire safety control [2, 3]. The main cause of fire in long regions of belt conveyors is the seizure of rollers and the friction between the roller shell and the loaded belt [4, 5]. The friction involves heating of the roller surface and heat emission, which can initiate inflammation of substances having the least burning point, for instance, coal dust [6].

Conveyor lines can be tens kilometers long, and the length of one conveyor can exceed one kilometer. The prompt detection of faults is difficult without special facilities [7, 8] as it is necessary to inspect each roller in the conveyor line, and the number of the rollers may exceed six thousand [9, 10]. The automated fire extinguishment systems are only provided at the power-drive and tension stations of conveyors and are absent along the conveyor flight.

A belt conveyor fire is an exogenous fire controllable using ventilation. Fire begins as inflammation initiated in off-normal mode of a conveyor, and has ultra early, early, developmental, mature and attenuated stages which differ by the ambient temperature. The ultra early and early fire detection enables early localization and elimination of an accident, without work interruption and any severe financial loss. The signs of an early fire can be the CO concentration