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Determination of Structural and Technological Parameters of the Cage Mills with Different Cross-Sections Grinding Chamber

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Abstract: The grinding process is one of the most fundamental in the production of building materials. The analysis of modern engineering and manufacturing technology of fine materials showed that crushers of cage mill with the implementation of internal classification of crushed materials have considerable prospects. In this regard, it is important to define the structural and technological parameters of cage mill units. In this study, we define the productivity of cage mills including grinding chamber with different cross-sections. Both the design parameters and the properties of the crushed material such as compressive strength, Young's modulus and others influence the productivity. In addition, the rotation frequency influences productivity too. It is generally known that the number of collisions of the particles of the material in the grinding chamber equals to the number of rows of impact elements, i.e., 4-5. Time which grinding particles spend in the chamber is 0.01-0.1 sec in average. To improve the efficiency of grinding in the cage mills it is necessary to increased residence time in the grinding chamber and the number of particle collisions with the working surface of the impact element. Various cross-section of the chamber leads to a change in grinding load on the grinding material which take the cyclical nature, the time of finding the particle material in the grinding chamber increases as well as the number of interactions of the material with impact elements which lead to improving the efficiency of a cage mill. A comparative analysis of the traditional grinding chamber of cage mill and grinding chamber with various cross-sections has been made. On the basis of theoretical and experimental data an advantage of the proposed cage mills with grinding chamber has been revealed.

Key words: Cage mill, classification, crushing, grinding chamber, impact elements, particle

INTRODUCTION

An important objective is to obtain a given particle size distribution of powders, the demand for which is increasing (Klochkov *et al*., 1982).

The relevance of research in this area is defined by big influence of the degree of crushing on technological properties of powders. Powders intended for filling of plastics, rubber, paper, cardboard, lime, chalk, kaolin, talc, alumina must possess a particularly high degree of dispersion. Studies of fine materials are more relevant because the increasing fineness, the grinding and separation become more difficult (Hodakov, 1972).

Empirically it was found that the observed change in the physico-chemical properties of the finely divided material can not be attributed solely to the decrease in particle size. It was found that along with the dispersion by mechanical crushing crystalline structure of the surface layers of the particles is undergoing significant changes. In the technological properties of fine powders are due not to dispersion but violations of the crystal structure (Andreev *et al*., 1980).

As a result of the experimental and theoretical studies in recent years in the world literature (Voronov *et al*., 2008a) new perspectives on grinding have developed. It is now believed that the grinding process is an extremely complex phenomenon where mechanical and physico-chemical factors have a great importance along with environment (Semikopenko *et al*., 2011).

It is necessary to improve the dispersion of the building and other materials in the form of the final product and the intermediate stages of processing into products demanded improvement and creation of new types of grinding machines.

Crushing of building materials is one of the most energy-intensive processes. Therefore, the correct selection of the chopper largely determines the efficiency of the production of building materials in general.

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High speed impact crushing characterized some features that in other cases could not be ignored. These include primarily change of the mechanical characteristics of the material at high strain rates. Another feature of the process of the fine crushing of materials is intensive wear of impact elements in the mills that require much time to replace them and permanently lost of a large amount of expensive high quality materials.

In recent years, intensive mills with a high speed impact: vibratory, fluid, cage mills and other types of them for the production of fine powders are designed.

Among the more promising of these machines are disintegrator mill which carried out a mechanical particle acceleration (Akkerman *et al.*, 1982).

In the grinding process intensification and extended durability of disintegrator optimally chosen motion path of the crushed material, length of the free flight of the particles, bandwidth, uniform loading and some other factors play a major role. All this is achieved by rational constructive solution, predetermined speed collisions of the particles which should decrease with increasing particle size and reach values sufficient to obtain the desired size distribution. Optimally selected bandwidth will reduce the specific energy consumption for grinding and reduce the specific wear of impact elements in mills. Achievement of high speed particle collisions with impact elements in cage mill at relatively low speeds of baskets leads to the creation of low ventilation effect and lower energy consumption for grinding (Bauman, 1973).

Despite the earlier research in the theory and design of disintegrants, currently there is no unified method of their calculation. This is due to the large variety of designs disintegrator which are based on different principles of crushing. In practice the constructive design of the disintegrants, the material of the working elements and mode of operation, mostly chosen empirically (Voronov *et al.*, 2008b).

Therefore, determination of structural and technological parameters of the cage mills with various cross-section grinding chamber is an important task.

MATERIALS AND METHODS

Productivity of cage mills is a key parameter in determining the efficiency of the grinding process and the work of the chopper (Klochkov *et al.*, 1982). At the same time the following parameters; n_1 and n_2 rotation frequency of rotors; d is diameter of the inner row of impact elements; l is the distance between adjacent impact elements of the inner row; k is number of impact elements of the inner row; D_{cp} and d_{cp} average particle size of the material before and after crushing; h is height of the impact element (in the light); (sigma) tensile strength of crushed material effect on the productivity of cage mill. Productivity as a function of all these parameters will be:

$$Q = f(n_1, n_2, d, l, k, D_{cp}, d_{cp}, h, [\sigma]) \tag{1}$$

The calculation of productivity accepts the hypothesis of bond; elementary work on grinding material is directly proportional to the increment of the parameter that is being ground between the geometric average volume and surface area of the finished product:

$$\Delta A = K\Delta\sqrt{VS} = K\Delta D^{2.5} \tag{2}$$

According to generalizing hypothesis elementary work on grinding of one piece is proportional to infinitely small change in some degree of its diameter D:

$$\Delta A_m = K_m \Delta D^{4-m} \tag{3}$$

where, m exponent determined empirically for the Bond formula m = 1.5. By differentiating the right side of the equation, we find the elementary work expended in grinding of one piece:

$$dA_m = K_m' D^{3-m} dD \tag{4}$$

Assume that a material having a volume Q_0, consists of equal-sized spherical pieces with a diameter D, the total number of pieces N, contained in the volume is defined by Eq. 5:

$$N = \frac{K_N Q_0}{\frac{1}{6}\pi D^3} = \frac{K'_N Q_0}{D^3} \tag{5}$$

and elementary work of the elastic forces at low strain the total volume Q_0 presents: $\Delta A_0 = N\, dA = K_N' (Q_0/D^3)\, K_m' D^{3-m}\, dD$; whence:

$$\Delta A_0 = \frac{K'_N K'_m Q_0 dD}{D^m} \tag{6}$$

To determine the total work A_0, expended on crushing the whole volume Q_0, it is necessary to consider when integrating the initial D_0 and the final d_k size pieces of raw material and grinding product.

After integrating the Eq. 6 from D_0 to d_k we obtain an equation for determining the productivity of cage mill:

$$\frac{A_0}{Q_0} = K_0\left(\frac{1}{d_k^m} - \frac{1}{D_0^{m-1}}\right);\ Q_0 = \frac{A_0}{K_0\left(\frac{1}{d_k^m} - \frac{1}{D_0^{m-1}}\right)} \quad (7)$$

For convenience, we denote K_0 through 10 W, where W-Bond work index, kW×h/t (Hodakov, 1972) then:

$$Q_0 = \frac{A_0}{10W\left(\frac{1}{d_k^{m-1}} - \frac{1}{D_0^{m-1}}\right)} \quad (8)$$

Considering that m = 1.5, obtain:

$$Q_0 = \frac{A_0\sqrt{D_0 d_k}}{10W\left(\sqrt{D} - \sqrt{d}\right)} \quad (9)$$

On the other hand, the work of the elastic forces:

$$A_0 = \frac{[\sigma]^2 V}{2E} \quad (10)$$

Where:

E = Young's modulus of the crushed material (MPa)

V = Volume of material to be ground, i.e., bandwidth of cage mill

Grinding material entering the grinding chamber, passes between the series of impact elements while the particle velocity vector is changed from the previous row to the next. We believe that this material completely fills the workspace between two adjacent impact elements.

To calculate the bandwidth disintegrator we believe that the amount of working space according to the design scheme is (Fig. 1):

$$V_0 = \frac{\pi l^2 h}{6}\mu \quad (11)$$

where, μ is loosening coefficient, equal 0.1-0.15. Volume of the inner space of the first row of the grinding chamber:

$$V_1 = V_0 k = \frac{\pi l^2 h\mu}{6} = \frac{\pi d}{(1+a)} \quad (12)$$

where, a side of the square cross-section impact element, m. Bandwidth of cage mills effects rotation frequency of rotors in grinding chamber. Therefore, bandwidth cage mill depending on the geometric parameters of the grinding chamber can be determined from the expression:

$$V = V_1 x = \frac{\pi^2 l^2 h\mu d}{6(1+a)}x \quad (13)$$

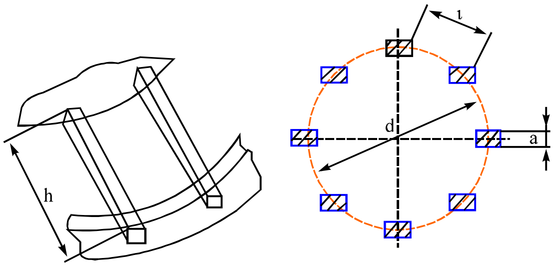

Fig. 1: Design scheme for determining bandwidth of cage mill. l = the distance between adjacent impact elements of the inner row; a = side of the square cross-section impact element, m; d = diameter of the inner row of impact elements

where, x parameter depending on the rotation frequency of the rotors and characterizing changes in productivity. In current sources (Bogorodskiy, 1982), it is recommended to determine the parameter x, based on the:

$$x^2 = n \quad (14)$$

Taking into account that in the cage mill two rotors rotate, possibly with different rotation frequency which significantly effect the performance, Eq. 14 takes the form:

$$x = \sqrt{n_1} \times \sqrt{n_2} = \sqrt{n_1 n_2} \quad (15)$$

where, n_1 and n_2 rotation frequency of rotors. Then the work of the elastic forces in view of the Eq. 10, 13 and 15 takes the form:

$$A_0 = \frac{[\sigma]^2 \pi^2 l^2 h\mu d\sqrt{n_1 n_2}}{12E(1+a)} \quad (16)$$

and Eq. 9 takes the form:

$$Q_0 = \frac{[\sigma]^2 \pi^2 l^2 h\mu d\sqrt{n_1 n_2}\sqrt{D_0 d_k}}{120WE\left(\sqrt{D_0} - \sqrt{d_k}\right)(1+a)} \quad (17)$$

Equation 17 describes the productivity of cage mill depending on the size of the starting material and takes into account both its properties and design features of cage mill.

It should be noted that the productivity of any grinder largely depends on the number of collisions with of impact elements the material being ground (Voronov *et al.*, 2008a). In disintegrator it is the number of collisions of impact elements of rotors with particles of the crushed material. Graphically, we denote it (Fig. 2) as the area of overlapped by the first row of impact elements, i.e.:

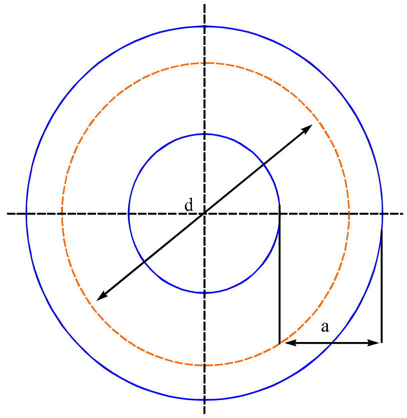

Fig. 2: Overlapped area by the first row of the impact elements disintegrator. a = side of the square cross-section impact element, m; d = diameter of the inner row of impact elements

$$A = \pi da \tag{18}$$

where, a side of the square cross-section of impact element, m. Through, a complex configuration of impact elements rows our cage mill's design allows to direct a part of the materials towards to the center of the grinding chamber, so to increase the number of repeated collisions with particles of the of impact elements of the crushed material and thereby increase productivity of cage mill in general.

To increase the number of collisions of particles with of impact elements of the material can also be possible due to the eccentrically arranged rows of impact elements with respect to axis of rotation of the rotors. The area overlapped by impact elements as shown in Fig. 3, will be equal to:

$$A = \pi d\left(a + 2e\right) \tag{19}$$

expressing d in Eq. 18 through Eq. 19 we will obtain:

$$d = \frac{d\left(a + 2e\right)}{a} \tag{20}$$

Then in the final result productivity of cage ills considering eccentrically located of impact elements will be:

$$Q = \frac{\sqrt{D_0 d_k}\left[\sigma\right]^2 \pi^2 l^2 h \mu d\left(a + 2e\right)\sqrt{n_1 n_2}}{120WE\left(\sqrt{D_0} - \sqrt{d_k}\right)\left(1 + a\right)a} \tag{21}$$

Analysis of Eq. 21 shows that decrease of the average size of the source material D_0 and increase the weighted average size of the finished product d_k effect cage mill. The increase in the geometric dimensions of the grinding chamber in cage mill, particularly increase the size of the impact elements "in light" also increases productivity. Increasing the rotation frequency of the rotors increases the yield d_k.

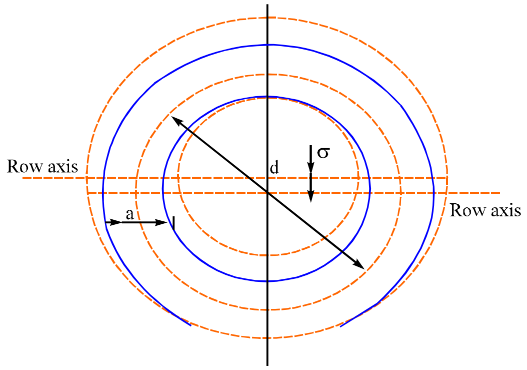

Fig. 3: Overlapped area by the first row of the impact elements in the form of an eccentric ring. a = side of the square cross-section impact element, m; d = diameter of the inner row of impact elements; **σ** = tensile strength of crushed material effect on the productivity of cage mill

By increasing the cross-sectional dimensions of impact elements productivity is reduced because the amount of space between the impact elements decreases.

It should be noted that the size of the square of the impact elements is limited by minimum gap between two adjacent impact elements which is equal to two maximum diameters of the particles of the grinding material (Semikopenko *et al*., 2011). We took limestone as the crushed material for which $\sigma = 4\times10^7$ Pa; $E = 3.5\times10^{10}$ Pa; $D = 0.01$ m.

The machine has the following geometrical parameters of the grinding chamber: $l = 0.02$ m; $h = 0.114$ m; $a = 0.12$ m; $W = 14$ kW×h/t; $\mu = 0.5$; $a = 0.01$ m; $e = 0.004$ m.

Let us consider the newly introduced parameter e-eccentricity between the center of the first row of the circle of impact elements relative to the axis of rotation of the rotor of grinding chamber.

If the axis of rotation of the rotors and the centers of the circles rows of impact elements do not match, the sectional area "in light" in the grinding chamber changes its value. Since, the relative rotation frequency of the rotors varies 3000-6000 min^{-1}, then change the workspace in a certain part of the grinding chamber is fleeting in nature. In connection with this there is an increase in the number of collisions of particulate material with impact elements and between themselves and the occurrence of crushing forces effect an increase in the destruction of material from the abrasive action of the forces which leads to an increase in grinding efficiency. It is believed that the particles of the crushed material as a result of one cycle perceive the number of collisions with impact elements equal to the number of rows in the last grinding chamber (Ushakov *et al.*, 1974). The proposed design of the grinding chamber allows to increase the number of particle collisions with material impact elements and each other due to the return of particles with subsequent rows on the previous ones but this material is exposed to intense cyclic test. It should be noted that the restriction of $e<e_{max}$ breakthrough is due to the possibility of particles through a rows of impact elements without collision. When e tends to zero, the nature of loads on the ground material will be a little different from the loads in traditional designs of cage mills.

RESULTS AND DISCUSSION

Dependence of the rotation frequency of rotors on productivity when e = 0 is shown on Fig. 4. The effect of the eccentricity on the productivity of the cage mill with eccentric rows of impact elements is shown in Fig. 5.

Taking into account theoretical and graphic studies we can conclude that the coarsening of the final product and increasing the rotation frequency of the rotors, the productivity increases. Essential performance is dependent on the particle size of the finished product. With decreasing fineness of the finished product the cage mill productivity performance decreases.

Reduction of the grinding degree with growth productivity is due to increased frequency of mutual collisions (Akkerman *et al.*, 1982).

With growth of the concentration of material particles in the grinding chamber the proportion of destroyed particles by mutual abrasion increases and destruction due to net impact reduces (Bauman, 1973). Productivity increases with the rotation frequency of one of cage mill rotors. Increasing the degree of grinding with growth rotor speed is due to the increased kinetic energy of the particle. In synchronous increasing speeds of both rotors productivity also increases.

It should be noted that with increasing rotational speeds of the two rotors more intensive increase productivity takes place than under the increase rotation frequency of one of them. Based on the relation (Eq. 14) we can conclude that the degree of grinding is a function of the kinetic energy of the particles of the crushed material.

Thus, application of cage mill rotors eccentric with row of impact elements improves the efficiency grinding material. With increasing eccentricity from zero to 0.002 m when $n_1 = n_2 = 62.5$ sec cage mill productivity on the final product d<100 m km growth from 71.36-99.9 kg h^{-1}.

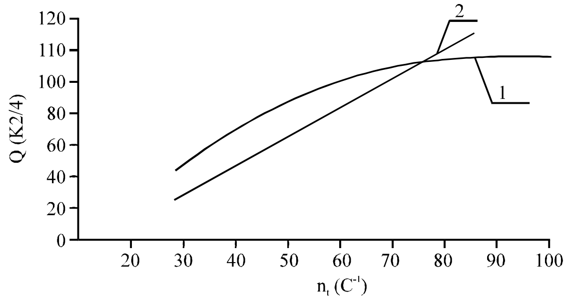

Fig. 4: Dependence of productivity (Q) on rotation frequency of rotors (n); 1: n_1 = 25-100 sec^{-1}; n_2 = const; 2: $n_1 = n_2$ = 25-100 sec^{-1}

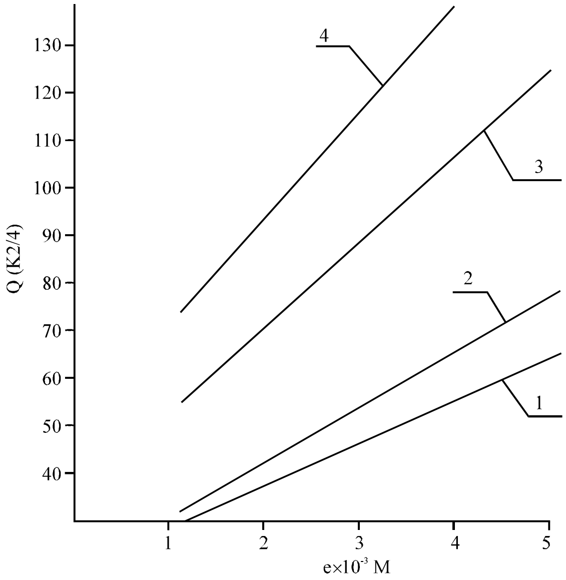

Fig. 5: Dependence of cage mill productivity on the axial displacement e; 1: d_k = 0.0001 m; 2: d_k = 0.0002 m; 3: d_k = 0.0003 m; 4: d_k = 0.0004 m

In accordance with the results it should be noted that the above construction of the grinding chamber of cage mill allows to provide qualitatively different load on the sample material which are cyclical (Akkerman *et al.*, 1982), while increasing the concentration of particles of the crushed material in the peripheral portion of the grinding chamber (Bauman, 1973). Material is crushed by abrasive loads (Gol'dshtik, 1981), crushing effect is created which leads to a significant increase in fineness of the finished product. By changing the value of the eccentricity we can adjust the amount of cyclic loading. When eccentricity is zero, the load on the sample material does not differ from the loads in traditional designs of cage mills (Khint, 1962).

The method of calculation productivity cage mills with an eccentric impact elements, taking into account the structural and technological features of the grinding chamber has been developed.

CONCLUSION

Crushing of building materials is one of the most energy-intensive processes. Therefore, proper selection of grinding largely determines the efficiency of production of building materials. The most promising type is cage mills which have a mechanical particle acceleration.

In this study, the method of calculation cage mill providing cyclic loads on the ground material with increasing the number of collisions of particles in the grinding chamber has been developed.

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