The compaction zone parameters’ determination when grinding the cement clinker particles

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Abstract. The article discusses the process of grinding cement clinker in a ball mill. A technique for determining the deformations parameters that the crushed particle receives when it interacts with the grinding body, is proposed. The relation for determining the maximum linear size of deformation during the grinding body’s interaction with the cement clinker particle is obtained. The expression for determining the grinding body contact area with the cement clinker particle is proposed. It is shown how the compaction zone is formed during the interaction of the grinding body with the crushed particle. The sealing zone has a cylindrical shape with the cylinder radius. It is shown that under the action of the introduced fracture energy by the grinding body, the material in the compaction zone starts expanding in the direction perpendicular to the impact force. This allows to determine the number of particles into which the cement clinker particle breaks up when hit by a grinding body.

1. Introduction
Modern construction is impossible to function without the use of building materials. The most common building material is concrete. The quality of concrete is primarily determined by the quality of the cement used, the production of which consumes significant energy resources [1-3]. One of the most energy-intensive processes in cement production is a fine grinding of the clinker with additives, which can spend on grinding from 40 kWh / t or more [1, 4-6].

The main grinding unit for grinding clinker and additives is a ball mill [1-3, 7]. It is used due to the simplicity of the design and its operation [1, 2]. To improve the quality of the cement obtained, a closed grinding cycle is widely used in the world [8-3]. To reduce the energy spent on grinding, it is necessary to understand the process of the grinding media interaction with the crushed medium. This will make it possible to optimally select the operating modes of the ball mill, the intra-mill filling, such as the type of lining, length of chambers, assortment of grinding media in chambers, etc.

The energy determination for grinding material in ball mills was discussed by various researchers. Their studies are presented in various works and publications [15-18]. However, not all of them allow sufficiently complete investigation of the grinding process of cement clinker and additives in ball mills. In [19], the work necessary for the destruction of the cement clinker elementary particle was determined depending on its size, generalized thermodynamic force, and elastic modulus of the crushed material. However, the issues of the grinding bodies sizes’ ratio, the crushed material, as well as the speed parameters of the interacting bodies are not considered.
2. Theoretical

To determine the parameters of the deformations that the milled particles receive, the following formulas relating to the geometric parameters of the grinding medium, clinker particles, their densities and speed parameters during grinding are presented. When developing this technique, let us suppose that the source material to be ground in the mill drum inside has a shape close to spherical. Let us take the radius of the spherical particle of the source material equal to \( R_2 \), and the radius of the grinding ball equal to \( R_1 \). If we consider the process of interaction of the grinding body with a particle of material based on the Hertz theory, according to the source [20], then the maximum linear strain size \( h \) during the interaction of the crushed material and the grinding body of a spherical shape is determined by the formula:

\[
h = \frac{15m_1m_2(v_1 - v_2)^2}{16(m_1 + m_2)\sqrt{R_1R_2}} \left[ \frac{1}{E_1} + \frac{1}{E_2} \right]^{2/5},
\]

where \( m_1, m_2 \) – denote the mass of the grinding ball and the crushed material, respectively, kg; \( E_1, E_2 \) – define the Young’s modulus of the grinding ball and the material particles (cement clinker), which take, respectively, the following numerical values: \( E_1 = 2.1 \times 10^{11} \) Pa, \( E_2 = 4.6 \times 10^{10} \) Pa; \( \mu_1, \mu_2 \) – denote the Poisson’s ratios for the grinding ball and grinding material, which are respectively equal: \( \mu_1 = 0.2...0.25, \mu_2 = 1/3 \); \( v_1, v_2 \) – are the speeds with which the grinding ball and material move, respectively, m/s.

In the calculations, we proceed from the assumption that the ball with the speed \( v_1 \) hits the ground material, and the relative velocity of the clinker particle is zero, i.e. \( v_2 = 0 \), then the relation (1) applied to a ball mill can be represented as:

\[
h = \frac{15m_1m_2v_1^2}{16(m_1 + m_2)\sqrt{R_1R_2}} \left[ \frac{1}{E_1} + \frac{1}{E_2} \right]^{2/5}.
\]

We transform the relation (2) as follows:

\[
h = \left[ \frac{15m_2v_1^2}{16\left(1 + \frac{m_2}{m_1}\right)\sqrt{R_2}} \right]^{2/5} A_1,
\]

where

\[
A_1 = \frac{1}{E_1} + \frac{1}{E_2} = (2.3895 \div 2.788)10^{-11}, \left( \frac{1}{\Pi \text{a}} \right).
\]

In the ratio (3), the masses of the grinding body (ball) and the grinding material (clinker) particles are expressed in terms of density and geometric size. Then:

\[
m_1 = \frac{4}{3} \pi R_1^3 \cdot \rho_1;
\]
\[
m_2 = \frac{4}{3} \pi R_2^3 \cdot \rho_2,
\]
where $\rho_2$, $\rho_1$ – define the density of the material and the grinding body (ball), the values of which can be taken respectively:

$$\rho_1 = 7.8 \cdot 10^3 \text{kg/m}^3; \quad \rho_2 = 3.3 \cdot 10^3 \text{kg/m}^3.$$ (7)

Taking into account the expressions (5) and (6), the relation (7) can be reduced to the following form:

$$h = \delta R_2.$$ (8)

Here the dimensionless quantity $\delta$ will be determined by the formula:

$$\delta = \left[ \frac{5}{4} \pi A_1 v_1^2 \rho_2 \frac{1 + \frac{R_2}{R_1}}{1 + \frac{R_2^3}{R_1^3} \frac{\rho_2}{\rho_1}} \right]^{2/5}. $$ (9)

The ratio obtained above makes it possible to determine the maximum linear size of deformation during the grinding body (ball) interaction with the cement clinker particle. The strain is proportional to the linear size of the material particle $R_2$ and in a complex way depends on the speed, linear size and density of the grinding body, as well as on the density and linear particle size of the cement clinker.

We introduce the following notation:

$$x = \frac{R_2}{R_1},$$ (10)

then, taking into account the equation (10), formula (9) takes the form:

$$\delta = \left[ \frac{5}{4} \pi A_1 v_1^2 \rho_2 \frac{1 + x}{1 + \frac{R_2^3}{R_1^3} \frac{\rho_2}{\rho_1}} \right]^{2/5}. $$ (11)

The analysis of the obtained dependence of the value $\delta$ from $x$ allows us to make the following conclusion. The dependency curve $\delta (x)$ for the indicated values $\rho_2$, $v_1$, $E_1$, $E_2$, $\mu_1$, $\mu_2$ has a local maximum corresponding to the value $x = x^*$, which, in turn, means that the magnitude of the cement clinker particle’s deformation will be the biggest, if the cement clinker particle’s geometric dimensions ratio to the size of the grinding body (ball) is equal to $x^*$.

According to the result of [21], the contact area of the grinding body with the material of cement clinker can be determined by the expression:

$$S = 2\pi R_2^2 - \pi R_2 \sqrt{4R_2^2 - R_2^2 \left( 2R_1 - h \right) \left( 2R_1 - h + h^2 \right)} \frac{4R_1 R_2 - 2R_1 h + 4R_2^2 - 4R_2 h + h^2}{R_2^2 \left( R_1 + R_2 - h \right)^2}. $$ (12)

We simplify the relation (12). Then the substitution of equation (9) into the formula (12) gives us the following view:
As it follows from the relation (11) when changing \( x \) in the range from 0.2 to 1, the equation value (11) is a small quantity. Therefore, the expression (12) can be simplified by taking into account the quantities of the first order of smallness with respect to \( \delta \). Taking into account the expression (10), accurate to the first-order small values, the relation (13) takes the form:

\[
S(x) \approx 2\pi R_2^2 \left\{ 1 - \sqrt{1 - 2\delta \frac{1 - \frac{x}{1 + x}}{(1 + \delta - x)^2}} \right\} \approx 2\pi R_2^2 \left\{ 1 - \sqrt{1 - 2\delta \frac{1 + x}{(1 + x)^2}} \left[ 1 - \frac{\delta x}{1 + x} \right]^2 \right\} \approx 2\pi R_2^2 \left\{ 1 - \sqrt{1 - \left( \frac{2\delta}{1 + x} \right)^2 \left( \frac{2\delta x}{1 + x} \right)^2} \right\} \approx 2\pi R_2^2 \left\{ 1 - \left( 1 - \frac{2\delta}{1 + x} \right)^2 \right\} \approx 2\pi R_2^2 \left\{ 1 - \left( 1 - \frac{\delta}{1 + x} \right) \right\} \approx 2\pi R_2^2 \left\{ 1 - 1 + \frac{\delta}{1 + x} \right\} \approx 2\pi \delta R_2^2. \tag{14}
\]

Thus, on the cement clinker particle spherical in radius \( R_2 \) by the area \( S(x) \), defined by the relation (14), the force \( F \) acts. Under the action of this force in the cement clinker particle with a radius \( R_2 \) a
sealing zone is formed having a cylindrical shape with a radius of the cylinder according to the formula (14):

\[ r = \frac{2\delta}{\sqrt{1+x}} R_2, \]  

(15)

and the height \( h \), which is given by the formula (8). According to the foregoing, the seal area will have a volume \( V_0 \), equal to:

\[ V_0 = \pi r^2 h = \frac{2\pi}{1+x} \delta^2 R_2^3. \]  

(16)

Fracture energy is introduced into this compaction zone \( Q_d \), equal to:

\[ Q_d = \frac{m_1 v_1^2}{2} = \frac{2}{3} \pi R_1^3 \rho_1 v_1^2, \]  

(17)

where \( v_1 \) – is the ball speed at the moment of contact with a cement clinker particle, m / s, which taking into account the separation angle of the grinding body, is determined by the expression:

\[ v_1 = \frac{3\pi}{5} R \sqrt{1+8\sin^2 a}. \]  

(18)

Here \( R \) – is the ball mill drum radius, m; \( \alpha \) – is an angle of separation of the ball from the mill drum (degree).

Under the influence of the destruction \( Q_d \) introduced energy in equation (17), the material in the compaction zone starts expanding in the direction perpendicular to the force of the action \( F \).

We find the ratio of the seal zone diameter to its height, according to the equations (15) and (8) and presented in the Figure:

\[ \frac{2r}{h} = \frac{\frac{2\delta}{\sqrt{1+x}} R_2}{\delta R_2} = \frac{2\sqrt{2}}{\sqrt{\delta(1+x)}}. \]  

(19)

Figure 1. Calculation schemes for determining the compaction zone: \( a \) – formation of a seal zone; \( b \) – comparison the geometric dimensions in the seal zone.
If in the equation (19) we put that \( x \leq 1 \), then, taking into account the quantity \( \delta \) smallness, we find that:

\[ 2r >> h. \quad (20) \]

Therefore, by the relation virtue (20), the compaction zone expansion as a result of the action of a generalized thermodynamic force \( f \) can be considered as the process of stretching the rod long \( 2r \) with the cross-section \( h \). Therefore, we can write that:

\[ \varepsilon_h = -\mu_2 \varepsilon_r, \quad (21) \]

where \( \varepsilon_h \) – is the sealing zone elongation in the transverse direction (direction \( h \)), but \( \varepsilon_r \) – defines the seal area elongation in the longitudinal direction (direction \( 2r \)).

3. Summary
As a result of the sealing zone expansion, the work, the value of which can be found if we use the formula to determine the elementary work, will be performed. To calculate the coefficient of energy expansion \( \alpha \), included in the equation for determining the elementary work, we calculate the change in the compaction zone volume during the infinitesimal process of energy \( Q_e \).

Thus, solving the equations (13) - (21) in common, we can determine the number of particles into which a cement clinker particle decays with a radius \( R_2 \) upon its collision with a grinding ball of radius \( R_1 \).

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