The definition of force parameters when grinding materials with anisotropic texture pressure in the press roller unit

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Abstract. The article deals with the issues of improving the efficiency of grinding materials with an anisotropic texture. The main specific features and conditions of the organization of the grinding process, including the conditions of loading materials with an anisotropic texture, the creating conditions of their directed motion and application of force load. The article explains the design of the press-roll unit (PRU) with a device for the directed supply of anisotropic materials is given, description its scheme and the process of work. The conditions of destruction of an anisotropic material between eccentrically mounted rolls are considered and an equation for the calculation of the specific force required for the destruction of anisotropic materials in eccentric rolls of PRU is obtained. The comparative data of values of specific values of crushing pressure at grinding of organogenic limestone obtained experimentally in PRU and by calculation are presented.

1. Introduction
Modern construction industry is based on the processing of great amount of materials with different mineralogical composition and physical and mechanical properties (clay, sand, limestone, granite, basalt, etc.). At the same time, the process of their grinding is accompanied by significant material and energy costs. It is known that about 10% of the world’s electricity is spent on crushing and grinding processes [1].

The increasing needs for processing of natural raw materials to create new building materials and mixtures, as well as the need to dispose of man-made dumps and waste of various industries will probably require even greater energy costs for grinding.

At the same time, the resource development of ores and other minerals tens of billions of tons of rocks are annually sent to the dump for storage, which in their mineralogical composition can be used in the production of a wide range of building materials. By the way, the extracted rocks differ from the traditional raw materials of the construction industry in their geological origin, mineralogical composition, texture and physical and mechanical properties. A special position among them is occupied by anisotropic materials characterized by various physical and mechanical parameters of the medium
(compressive resistance, tensile strength, bending strength, Young's modulus, shear strength, Poisson's ratio, dielectric, magnetic permeability, etc.) table 1.

Much research of scientists has been done [2-4] confirm the direct dependence of the anisotropy coefficient $\hat{E}_{an}$:

$$\hat{E}_{an} = \frac{\sigma_1}{\sigma_2},$$  \hspace{1cm} (1)

where $\sigma_1, \sigma_2$ - respectively, the tensile strength of an anisotropic material in directions perpendicular and parallel to the banding mineral structure.

These circumstances determine the great attention of scientists and experts to the development of their processing technology and the constructive improvement of crushing and grinding equipment for the purpose save energy when grinding materials with anisotropic texture. In this regard, a special relevance arises in the directional and uniform suppl of aggregates uses for the destruction of materials with anisotropic texture, as it is possible to provide a directed force on the crushed material in the direction of its lowest strength, which will significantly reduce the energy consumption for grinding.

2. Main part

When crushing anisotropic rocks, the efficiency of the destruction process is determined by many factors: the strength characteristics of materials, their structural and textural characteristics and, most importantly, the method and direction of application of destructive forces. The analysis of scientific and technical researches of processes of destruction of isotropic and anisotropic materials in various crushing and grinding units shows that at the organization of process of crushing of anisotropic materials it is necessary to consider not only their specific features, but also conditions of the organization of the process:

- conditions of loading of materials with anisotropic structure and their ordered motion;
- the direction of force application;
- process flowsheet of organization the process of grinding materials at each stage of their processing.

| Material short text | Compressive resistance, MPa | Coefficient of anisotropy |
|---------------------|-----------------------------|--------------------------|
|                     | Perpendicularly slaty cleavage | Parallely slaty cleavage |                        |
| Limestones, organogenic | 95                          | 65                       | 1.46                    |
| Metamorphic shists (land deposit Kursk Magnetic Anomaly) | 130                          | 59                       | 2.2                     |
| Amphibolite (land deposit Kursk Magnetic Anomaly) | 145                          | 75                       | 1.93                    |
| Quartzite sandstone banded | 260                          | 190                      | 1.37                    |

The existing range of crushing equipment both in Russia and abroad does not take into account the features of the crushed raw materials.

The analysis of the conditions of the movement of the material and its grinding compression in the press-roll units indicates the feasibility of the use of feed devices roll type, which provide a uniform distribution of the charge layer across the width of the working bodies of PRU, its effective pre-compaction and directed supply of the material layer in the inter-roll space. At the level of the invention, we have developed the construction design of a press-roll unit with a device for the directed supply of anisotropic materials. (Figure 1).

The press-roll unit consists of rolls 1, 2 eccentrically mounted on the frame, over which the roll device is located inside the bin, consisting of two movable cheeks 5, in contact with the rollers 3,4, connected to each other by guide leverage. The principle of operation of the unit. The material having
an anisotropic texture, for example, organogenic limestone and others, is fed to receiving bin, where it is fed to the rolls 3 and 4 along the movable cheeks 5, captured by them, rotated in a forward-rearward location, compacted, evenly distributed across the width of the rolls and sent to the inter-roll space.

Further, the material is captured by eccentric rolls 1, 2, where its crush-shearing deformation is realized, due to the different circumferential speeds of the working surfaces of the rolls. The opening between the spring-actuated rolls 3, 4, determined within the magnitude of the value $H = R_{av} (1 - \cos \alpha) + \delta$ (where $\alpha$ - angle of the rolls, $R_{av}$ - average radius of the rolls, $\delta$ - eccentric roll opening). (Figure 1)

![Figure 1. Press-roll unit with a device for directed supply of anisotropic materials: a – photo of the experimental setup, b – scheme of work.](image)

Field researches confirmed the performance capability, construction design of PRU and high efficiency from the use of materials with an anisotropic texture when grinding.

However, the complexity of the implementation of these units in production is largely determined by the lack of a method for calculating the magnitude of the effort required for the destruction of anisotropic materials. Press roller units with eccentrically mounted rollers allow implementing effective conditions of crush and shear directional force on anisotropic material.

The force effect realized between eccentric rolls depends largely on size of the grinding force applied area, which is limited to certain angles, which have a significant impact not only on the amount of material they capture, but also on the output process parameters. Therefore, the determination of the magnitude of the angles in the eccentric rolls is the important task when calculating the force of grinding materials in the press-roller units.

It has been established that a layer of particles with an anisotropic texture during the process of grinding particles in PRU with eccentric rolls and device for directional feeding, first undergoes directional movement, width distribution and compaction by the device rollers [7-10] (Figure 2), and then compacted and oriented particles of it in a uniform layer along the thickness $h_{com}$ and width $B$ of the rolls are fed into the inter-roll space. Entered into the zone of capture of material $\alpha_{def}$, material undergoes deformation between eccentrically mounted rolls, where they are subjected to crushing-shear deformation at variable radii and peripheral speeds of the working surfaces of the rolls.
Maximum grinding forces for grinding material is achieved in the zone of neutral angle $\alpha_n$ (Figure 2) and the elastic expansion of the compressed particles, facilitating the release of materials from the inter-roll space, is limited by the angle of elastic expansion $\alpha_{com}$.

With equality when $R_1 = R_2 = R$ ($e = 0$) the width of the zone of capture of the material rolls equal to:

$$H_0 = 2R - 2R\cos\alpha_{defR} + \delta = 2R(1 - \cos\alpha_{defR}) + \delta.$$  \hspace{1cm} (2)

Then the roll deformation angle is:

$$\alpha_{defR} = \arccos\left(1 - \frac{H_0 - \delta}{2R}\right) = \arccos\left[1 - \frac{\delta(k_{com} - 1)}{2R}\right], \quad k_{com} = \frac{H_e}{\delta}. \hspace{1cm} (3)$$

Accordingly, the current value of the layer thickness in the particle deformation zone, its elastic expansion are equal to:

$$H_{com,\alpha} = 2R(\cos\alpha_{defR} - \cos\alpha_0), \hspace{1cm} (4)$$

$$H_{com,\alpha} = 2R(\cos\alpha_{comR} - \cos\alpha_0). \hspace{1cm} (5)$$

Determine the magnitude of the deformation angles for eccentrically mounted rolls, when $e_1 = e_2 = e$. From right-angled triangles, radius constrained $R_1 = O_1A$ and $R_2 = O_2B$ and verticals lowered to horizontal axes $K_1$ and $K_2$ when $R_1 = R_2 = R$, there is as result

$$AK_1 = B\hat{K}_2 = R\sin\alpha_{defR}.$$

When the eccentric rolls are in a position where the eccentricity values are maximum and opposite from the triangles $\triangle O_1AK_1$ and $\triangle O_2BK_2$ arise from:

$$AK_1 = \left(R\cos\alpha_{defR} + e\right) \cdot \tg\alpha_{defR \ Re 1}, \hspace{1cm} (6)$$

$$B\hat{K}_2 = \left(R\cos\alpha_{defR} - e\right) \cdot \tg\alpha_{defR \ Re 2}. \hspace{1cm} (7)$$

Then measure of the angles of roll deformation equals:

$$\tg\alpha_{def \ Re 1} = \frac{AK}{R\cos\alpha_{defR} + e} = \frac{R\cos\alpha_{defR}}{R\cos\alpha_{defR} + e}; \hspace{1cm} (8)$$

$$\tg\alpha_{def \ Re 2} = \frac{BN}{R\cos\alpha_{defR} - e} = \frac{R\cos\alpha_{defR}}{R\cos\alpha_{defR} - e}$$

or

$$\alpha_{def \ Re 1} = \arctg \frac{R\cos\alpha_{defR}}{R\cos\alpha_{defR} + e}; \hspace{1cm} (9)$$
\[
\alpha_{\text{def} \, R_{e2}} = \arctg \frac{R \cos \alpha_{\text{def}R}}{R \cos \alpha_{\text{def}R} - e}.
\]  

(10)

With the aim of measuring neutral angles, consider the forces acting in the zone of the neutral angle \(\alpha_n\) (Figure 3). In the same zone, an elementary area is acted upon by a maximum pressure force. \(P_{\text{max}}\) and roll friction \(P_f\), which can be written as:

\[
dP_{\text{max}} = D_{\text{max}} \cdot B R_1 d\alpha_{n_1} = D_{\text{max}} \cdot B R_2 d\alpha_{n_2};
\]

\[
dP_f = f \cdot D_{\text{max}} \cdot B R_1 d\alpha_{n_1} = f \cdot D_{\text{max}} \cdot B R_2 d\alpha_{n_2},
\]

(11)

where \(B\) - roll width, m; \(f\) - coefficient of external friction.

The equilibrium equation of elementary forces acting in the zone of a neutral angle can be written as:

\[
- \int f_{\alpha_{a_1}} \cdot D_{\text{def}1} \cdot B_1 \cdot R_1 \cdot \cos \alpha_i \cdot d\alpha_i + \int f_{\alpha_{a_1}} \cdot D_{\text{def}1} \cdot B_1 \cdot R_1 \cdot \cos \alpha_i \cdot d\alpha_i + \int f_{\alpha_{a_1}} \cdot D_{\text{def}2} \cdot B_2 \cdot R_2 \cdot \cos \alpha_i \cdot d\alpha_i + \int f_{\alpha_{a_1}} \cdot D_{\text{def}2} \cdot B_2 \cdot R_2 \cdot \cos \alpha_i \cdot d\alpha_i = \int f_{\alpha_{a_2}} \cdot D_{\text{def}1} \cdot B_1 \cdot R_1 \cdot \sin \alpha_i \cdot d\alpha_i - \int f_{\alpha_{a_2}} \cdot D_{\text{def}1} \cdot B_1 \cdot R_1 \cdot \sin \alpha_i \cdot d\alpha_i - \int f_{\alpha_{a_2}} \cdot D_{\text{def}2} \cdot B_2 \cdot R_2 \cdot \sin \alpha_i \cdot d\alpha_i - \int f_{\alpha_{a_2}} \cdot D_{\text{def}2} \cdot B_2 \cdot R_2 \cdot \sin \alpha_i \cdot d\alpha_i.
\]

(12)

\[\begin{align*}
\alpha_{\text{def}1} & = D_{\text{def}1} \\
\alpha_{\text{def}2} & = D_{\text{def}2} \\
\alpha_{a_1} & = \alpha_{a_2}
\end{align*}\]

Figure 3. Schematic illustration for the calculation of neutral angles.

Considering that in the zone of neutral angle \(D_{\text{def}1} = D_{\text{def}2}, B_1 = B_2\), which are constant, then after rearrangement we get:

\[
\begin{align*}
\int f_{\alpha_{a_1}} \cdot \cos \alpha_i \cdot d\alpha_i + \int f_{\alpha_{a_1}} \cdot \cos \alpha_i \cdot d\alpha_i = \\
\int f_{\alpha_{a_2}} \cdot \cos \alpha_i \cdot d\alpha_i - \int f_{\alpha_{a_2}} \cdot \cos \alpha_i \cdot d\alpha_i - \int \sin \alpha_i \cdot d\alpha_i - \int \sin \alpha_i \cdot d\alpha_i.
\end{align*}
\]

(13)
Integrating and tailored $\alpha_{\text{def}1} = \alpha_{\text{def}R1}$ (8) and $\alpha_{\text{def}2} = \alpha_{\text{def}R2}$ (9) equalization (12) can be written as:

$$\alpha_{n1} + \alpha_{n2} = \frac{1}{4f_{\alpha_n}} \begin{bmatrix} \arctg \left( \frac{R \cos \alpha_{\text{def}R}}{R \cos \alpha_{\text{def}R} + e} \right) + 2f_{\alpha_n} - \arctg \left( \frac{R \cos \alpha_{\text{def}R}}{R \cos \alpha_{\text{def}R} + e} \right) \\ + \arctg \left( \frac{R \cos \alpha_{\text{def}R}}{R \cos \alpha_{\text{def}R} - e} \right) \end{bmatrix} + \frac{1}{4f_{\alpha_n}} \begin{bmatrix} \arctg \left( \frac{R \cos \alpha_{\text{def}R}}{R \cos \alpha_{\text{def}R} + e} \right) + 2f_{\alpha_n} - \arctg \left( \frac{R \cos \alpha_{\text{def}R}}{R \cos \alpha_{\text{def}R} - e} \right) \end{bmatrix}. \quad (14)$$

After passing the zone of maximum effort $P_{\text{max}}$ is the result an elastic expansion of the layer of crushed particles occurs in the zone of the angle of elastic expansion, the value of which can be determined by the radius $R = R_{av} = \frac{(R + \delta) + (R - \delta)}{2}$ (where $\epsilon$ – current eccentricity value) by analogy with (2):

$$\alpha_{\text{comR}} = \arccos \left[ 1 - \frac{\delta'(k_{\text{com}} - 1)}{2r} \right]. \quad (15)$$

where $\delta'$ - the thickness of the layer of particles after its elastic expansion, m; $k_{\text{com}}$ - coefficient of elastic expansion,

$$k_{\text{com}} = \frac{\delta'}{\delta}. \quad$$

To determine the specific grinding force, we consider the conditions for the destruction of anisotropic material between eccentrically mounted rolls, assuming that the normal stresses in the anisotropic material are uniformly distributed along the roll arc in the deformation zone, and the greatest grinding efforts are achieved along the line connecting the centers of the rolls to the neutral zone of action angle rolls.

**Figure 4.** Schema forces for determining the forces grinding.

The sum of projections of forces, arising in the elementary layer on the coordinate axis "x" and "y" is equal to:

$$\sum F_x = 0, \quad R_{e1} q_1 d\alpha_{\text{def}} \cos \alpha_{\text{def}} + R_{e1} q_1 d\alpha_{\text{def}} f \sin \alpha_{\text{def}} - \delta_x dy = 0; \quad (16)$$

$$\sum F_y = 0, \quad \delta_y h_x - (\delta_y + d\delta_y) h_x + d\delta_y h_x + dR_{e1} q_1 d\alpha_{\text{def}} \sin \alpha_{\text{def}} - f R_{e1} q_1 d\alpha_{\text{def}} \cos \alpha_{\text{def}} = 0. \quad (17)$$
where $R_1$ - the radius of the roll, m; $q$ - specific force, arising on the surface of the roll, N/m$^2$; $\alpha_{def}$ - the angle degree of deformation; $f$ - coefficient of external friction; $\delta_x$ - direct stress, arising in the deformable layer, N/m$^2$.

After the corresponding transformations and differentiation, we obtain an equation for calculating the specific force required for the destruction of anisotropic materials in eccentric rolls of PRU.

$$D_1 = \frac{0.71 fL\alpha_k \sigma_{sz}}{k_{un}} (tg\gamma - f_T) le ^{-SG_{cos\alpha}} \cdot \frac{H_0 \cdot tg\alpha_{def}}{\Delta h f(\delta - tg\alpha_{def})} \cdot \left[1 + \frac{f_0}{tg\alpha_{def}} \left(1 - \frac{2(\delta_{def} - \delta)}{H_0} \right) \left(\frac{\alpha_{def} - f_0}{tg\alpha_{def}} \right) \left(\frac{H_0}{h_{def}} \right)^{\frac{1}{tg\alpha_{def}}} \right].$$  \hspace{1cm} (18)

where, $G_{sz}$ - ultimate resistance anisotropic media under compression, N/m$^2$; $tg\alpha_{def}$ - angle of deformation of the batch layer; $f$, $f_T$ - respectively, the coefficient of internal and external friction; $S$ - the area of the crushing chamber, m$^2$; $L$ – the perimeter crushing cavity, m; $\alpha_k$; $\xi$ - coefficient side thrust; $tg\gamma$ - the average value of the angle of inclination of the contact area of anisotropic particles to three mutually perpendicular coordinate axes; $H_o$ - the thickness of the layer of particles at the beginning of deformation, m; $\Delta h$ - deformation of the batch layer during its destruction, m; $k_{un}$ – anisotropy factor of material; $\alpha$ - the angle of maximum effort; $\delta$ - gap of the roll opening, m.

From the graphical dependence (Figure 5) built on the equation (17) showed that the increase in the radius of the rolls entails an increase in the grinding force. This indicates that an increase in the radius of the rolls leads to an increase in the thickness of the layer of material captured by the rolls and the area of the maximum force zone, and, consequently, L and S, requires large grinding forces.

![Figure 5](image_url)

Figure 5. The influence of the inverted divisor of the radius of the rolls on the specific fracture pressure in the PRU of anisotropic materials with different compressive strength.

Grinding forces also increase with the growth of the initial strength of the crushed material, which makes it possible to make an important conclusion for practice that when grinding anisotropic materials it is necessary to create a force effect in the direction of their lowest strength. This requires the development of a device that carries out their directed supply to the rolls of PRU.
3. **Summary**
   Thus, it was found that:
   - the force effect that occurs between the eccentric rolls depends largely on the size of the site of application of grinding forces, which is limited to certain angles, which have a significant impact not only on the value of the captured piece of material, but also on the output indicators of the process.
   - layer of particles with an anisotropic texture in the process of grinding it into PRU with eccentric rolls $h_{com}$ and device for directed feeding $B$, is first subjected to directional movement, width distribution and compaction by the rollers of the device, then the compacted and oriented particles are fed into the inter-roll space with a uniform layer in thickness and width of the rolls.
   
   The material received in the capture zone $\alpha_{def}$ is subjected to deformation between eccentrically mounted rolls, where they are crushed and shear deformation at variable radii and circumferential speeds of the working surfaces of the rolls.

4. **Conclusion**
   As a result of analytical studies, the equations for calculating the value of the angular parameters are obtained:
   - the force effect realized in eccentric rolls when grinding materials with an anisotropic texture depends not only on the construction design of the working bodies, but also on the force application.
   - in the article obtained an equation that allows us to determine the value of the current resistance of the crushing-shear deformation of the charge layer based on the geometric parameters of the press-roll grinder with eccentric rolls and physical and mechanical characteristics of the crushed anisotropic material. The comparison of the specific values of the grinding pressure in the grinding of organogenic limestone ($G_{sz} = 95 \, \text{N/m}^2$), available from experiments in PRU with $R = 0.5 \, \text{m}$, is $141 \, \text{MPa}$ and by means of a calculation is $148.6 \, \text{MPa}$, showed that the discrepancy does not exceed $10\%$. Thus, the obtained equation (16) with adequate accuracy reflects the real process.

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