Increase of size reduction of materials with anisotropic texture

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Abstract. This article presents the results of the analysis of the process of grinding of materials with anisotropic structure and a new approach is proposed to increase of its efficiency.

1. Main part

In the extraction of ore and non-metallic minerals, tens of billions of tons of rocks are sent annually to the dumps for storage, which in their mineralogical composition may well be used in the production of a wide range of building materials. Simultaneously mined rocks differ from the traditional raw materials of the construction industry in their geological origin, mineralogical composition, texture and physical and mechanical properties.

Iron ore deposits, mining which is carried out in an open way, contain dumps of simultaneously mined rocks, polluting the environment, removing fertile soils from the agricultural turnover and requiring significant material costs for their maintenance. Only in the fields of KMA their volume is about 1 billion m³, a significant part of these rocks is anisotropic materials.

Anisotropic materials characterized by different physical and mechanical parameters of the medium (compression strength, tensile strength, bending strength, young's modulus, shear strength, Poisson's ratio, dielectric strength, magnetic permeability, etc.) are characterized by particularly different strength characteristics depending on the direction of application of the force. (Table 1)

| Name of material               | Compressive strength, MPa | Anisotropy factor |
|--------------------------------|---------------------------|------------------|
|                                | Perpendicular to schistosity | Parallel to schistosity |
| Limestones organogenic         | 95                        | 65               | 1.46          |
| Metamorphic shale (KMA Deposit)| 130                       | 59               | 2.2           |
| Amphibolites (KMA Deposit)     | 145                       | 75               | 1.93          |
| Quartzite-sandstones striped   | 260                       | 190              | 1.37          |

This, in turn, imposes additional requirements on the conditions of grinding of anisotropic materials, and, consequently, on the design and technological parameters of crushing and grinding equipment. In connection with the development of modern technologies, there is a need to modernize existing and create new units and technologies for coarse and fine grinding of anisotropic materials,
widely used in the production of various building materials and products.

Currently, there is a huge amount of crushing and grinding equipment of not only different design, but also the principles of action and methods of destruction of materials. For example, the destruction by crushing is carried out in roll and medium-pass mills. In units of impact action, material is destroyed by the impact of hammers or beat moving at high speed. In jet mills, grinding is carried out by the collision of particles against each other, moving in the stream under the action of energy or on the wall of the unit.

However, when grinding anisotropic rocks, the efficiency of the destruction process is determined by many factors: the strength characteristics of the materials, their structural and texture characteristics and the main method and direction of application of destructive forces. Analysis of scientific and technical studies of the processes of destruction of isotropic and anisotropic materials in various crushing and grinding units [2,3] shows that the organization of the process of grinding anisotropic materials must take into account not only their specific features, but also the conditions of the process:

- loading materials with anisotropic structure and direction of their movements;
- direction of weight training;
- technological schemes of the organization of processes of grinding of materials at each stage of their processing (classification of crushed products, internal and external recycling of crushed materials, separation of fine particles, etc.);
- implementation of effective design and technological solutions that improve the wear resistance of the working bodies of the equipment and its operational reliability, etc.

The analysis of crushing and grinding equipment structures and rational conditions of destruction of anisotropic materials shows the feasibility of using press-roller shredders for these purposes [1], which have a number of advantages: simplicity of design and reliability of operation, high performance and low specific energy consumption, low metal content and high-speed parameters of working bodies, the possibility of their further structural and technological improvement taking into account the specific features of the material to be ground, etc.

In recent years, grinding materials of different strengths in many industries have widely used press roller shredders working on various technological schemes. Analysis of scientific and technical literature [2,4,5] shows that PVA is used both in open and closed grinding cycle during grinding of limestone, clinker, slag, lime, quartz, coal, ore materials. At the same time, the specific energy consumption in the grinding complex "PVA-TSHM" is reduced by 20-40% and its productivity is increased by 15-40%.

The analysis of scientific and technical developments in the field of creation and structural and technological improvement of PVA testifies, on the one hand, to the wide use of this technological equipment for pre-grinding of isotropic materials with different physical and mechanical characteristics, and on the other hand, to the need to establish the basic laws of the process of grinding of anisotropic materials in PVA and their further structural and technological improvement, taking into account the characteristics of the crushed rocks.

The conditions of force action in the destruction of fragile bodies of anisotropic texture largely determine the performance of the grinding process. Therefore, the choice of the geometric shape of the working bodies of the unit and the conditions for the application of power loads are an important reserve for both structural and technological improvement of the equipment and the formation of the technological process as a whole.

The destruction of fragile bodies undergoes elastic, brittle and plastic deformation. Let’s consider the scheme of power effects on the brittle bodies destroyed, implemented in the rolls of PVA (Figure 1). The simplest case of destruction of a solid body is the force between two parallel surfaces, for example, cylindrical rolls of the same diameter and rotating at the same circumferential speed (Figure 1, a).

In the points of contact of the working surface of the rolls with the material there are crushing
forces \( P\sigma_1, P\sigma_i \) from the first and second rolls: 

\[
P\sigma_1 = \sum_{i=1}^{n} P(P\sigma_1...P\sigma_i) ,
\]

which until the moment of its destruction are balanced by reactions \( N_1, N_i \), from the material side in the direction of the rolls:

\[
N_1 = \sum_{i=1}^{n} (N_1...N_i) ; \quad N_2 = \sum_{i=1}^{n} (N_1...N_i).
\]

When the balance of the deformable body, the conditions are met:

\[
P\sigma_2 = \sum_{i=1}^{n} (P\sigma_1...P\sigma_i) = \sum_{i=1}^{n} (N_1...N_i).
\]

**Figure 1. A scheme of impacts aimed to destroy the fragile body**

When applying a destructive force at an angle \( \alpha \) to the work surface \( P\sigma_1, \tau \) (Figure 1, b) (this can be achieved when using eccentric rolls or rolls with different diameters), the deformable body is subjected to a crushing and shear effect on the part of the forces \( P\sigma, \tau \) and their components \( P\sigma_i, \tau \).

When increasing the angle of inclination \( \alpha \) of the external force \( P\sigma_1, \tau \), the value of the shear deformation \( P\tau_1, ... P\tau_i \) increases with a corresponding decrease in the values of crushing forces \( P\sigma_1, ... P\sigma_i \). When the balance of the deformable body meets the condition:

\[
P\sigma_1, \tau = \sum_{i=1}^{n} (P\sigma_1, P\sigma_i) \cos \alpha = \sum_{i=1}^{n} (N_1...N_i).
\]

The most complex force effect on the deformable body is observed when applying forces to the surface of the destroyed piece of material at different angles in different planes \( \alpha \) and \( \gamma = R_{\min}/R_{\max} \) (for example, realized in conical rolls due to the profile implementing different circumferential speeds of the surfaces along the width of the rolls) (Figure 1, c, d):
\[ N_1 = P \sigma_1 \cos \alpha + \tau_{\Sigma 1} \sin \alpha + \tau_{\Sigma 1 \gamma} \cos \frac{R_{\text{min}}}{R_{\text{max}}}; \]

\[ N_2 = P \sigma_2 \cos \alpha + \tau_{\Sigma 2} \sin \alpha + \tau_{\Sigma 2 \gamma} \cos \frac{R_{\text{min}}}{R_{\text{max}}}. \]

When exposed to the force load \( P \sigma_{\Sigma} \) on the normal to the working surface of the destructive body, it is the most simple scheme of crushing action (Figure 1, a).

When the load \( P \sigma_{\Sigma} \) is applied at an angle \( \alpha \) to the normal, the crushing-shear deformation of the destroyed body is realized (Figure 1, b).

Force \( P \sigma_{\Sigma} \) at an angle \( (\alpha, \gamma) \) (Figure 1, c, d) (created by the conical profile of the surface of the rolls) to the normal allows for the bulk-shear deformation of the body. Such impact is preferable for materials with an anisotropic structure, since it allows its destruction in the direction of shale (its lowest strength), which leads to its destruction with less effort and energy. This factor is of particular importance for anisotropic shale (layered, striped) structure bodies exposed to shear deformation and formation of lamellar plates.

In real conditions of material layer grinding, the process of solid body deformation is much more complicated, as the destruction is carried out not only under the influence of forces directed in the above-mentioned directions, but also because of the contact with each other pieces of material having a more complex surface and different strength, and their force action is oriented along different axes. [6]

Let us suppose that an anisotropic solid is deformed by a destructive force \( P \sigma_{xy}, \tau_{xy} \) directed to the Z axis at an angle \( \alpha \) (Figure 2).

Accordingly, there are normal \( P \sigma_{xy} = P \sigma_{xy} \cdot \tau_{xy} \cdot \cos \alpha \) and tangent \( P \tau_{xy} = P \sigma_{xy} \cdot \tau_{xy} \cdot \sin \alpha \) components. In turn, the tangent component provides shear deformation of the body layers along the x-axis \( P \tau_x = P \tau_{xy} \cdot \cos \gamma \) and the y-axis \( P \tau_y = P \tau_{xy} \cdot \sin \gamma \).

Figure 2. The scheme of deformation of the solid anisotropic texture in the rolls of the press roller grinder
The resulting force $P\sigma_{xy} \tau_{xy}$ causes the reaction of the opposing $N_{xy}$, and tangential (shear) component of the friction force $F_{tp} = fN_{xy} = P\tau_{xy}$. The presence of two oppositely directed forces $P\tau_{xy}$ and $F_{tp}$ leads to the appearance in the cross section of the deformable body of two sites $S_{adv}$ and $S_{tp}$, which act in the opposite direction of the shear stresses $\tau_{xy,adv}$ and $\tau_{xy,tp}$.

The deformable body will be in equilibrium (not destroyed) if the normal and tangential stresses are balanced, i.e. the value of the deformable force $P\sigma_{xy}$ will be less than or equal to the ultimate compression strength of the body, and the value of the shear force $P\tau_{xy}$ will not exceed the internal adhesion force of the layers of the deformable body:

$$\begin{cases}
P\sigma_{xy} = P\sigma_{xy} \tau_{xy} \cos \alpha \leq \int \sigma \ dS, \\
P\tau_{xy} = P\sigma_{xy} \tau_{xy} \sin \alpha \leq \int \tau \ dS.
\end{cases} \tag{1}$$

Given that for anisotropic bodies the shear forces are the most dangerous $P\tau_{xy}$ which depend, in turn, on the angle $\alpha$ of inclination and the absolute value of the resulting $P\sigma_{xy}, \tau_{xy}$, the equilibrium state $F_{tp} = fN_{xy} = P\tau_{xy}$ can be achieved only by redistributing the areas of the $S_{adv}$ and $S_{tp}$, which are the shear stresses $\tau_{xy,tp} = \frac{F_{tp}}{S_{tp}}$ and $\tau_{xy,adv} = \frac{P\tau_{xy}}{S_{adv}}$, but with different signs.

The equilibrium state will be observed under the condition:

$$P\tau_{xy} \sin \alpha = \int_{S_{tp}} \tau_{xy,tp} dS - \int_{S_{adv}} \tau_{xy,adv} dS = \tau(S - 2S_{adv}) \tag{2}.$$  

With increasing shear forces $P\tau_{xy} = P\sigma_{xy} \tau_{xy} \sin \alpha$, the value of $S_{adv}$ will increase and $S_{tp}$ decrease. When reaching $S_{tp} = 0$, the value $P\tau_{xy}$ reaches the maximum and the equilibrium is disturbed, the deformable body will move along the plane of sliding XY. Contact stresses $\tau_{adv}$ will be oriented in one direction, against the direction $\tau_{tp}$. Given there is limited movement of the body in space (due to the presence of other bodies), the most favorable conditions for the destruction of the body along the planes of stratification appear.

According to Coulomb’s law:

$$F_{tp} = (aN_{xy} = fP\sigma_{xy} \tau_{xy} \cos \alpha) = f \int \sigma_{sp} S = f \sigma_{sp} S \tag{3}$$

and solving equations (1) and (2) together, we obtain $f = \frac{P\sigma_{xy} \tau_{xy} \sin \alpha}{P\sigma_{xy} \tau_{xy} \cos \alpha} = \tan \alpha$. Or, expressing the coefficient of friction $f$ through normal and tangential stresses, taking into account the formula (3), we obtain:
\[ f = \frac{F_{ip}}{N} = \frac{\tau(S - 2S_{sdv})}{\sigma_{sp}S} = \tan \alpha, \quad \text{or} \quad \alpha = \arctan \frac{\tau(S - 2S_{sdv})}{\sigma_{sp}S} \tag{4} \]

Analysis of formula (4) shows that in case of equality of the tangential and normal stresses \( \tau = \sigma_{sp} \) and \( S_{sdv}=0 \), the maximum value of the friction coefficient \( f = 1 \) is achieved at \( \alpha = 45^\circ \). It follows an important conclusion that to reduce the formation of flaky pieces of material in the destruction of an anisotropic body, the angle of application of the destructive force should not exceed 45°. However, when applying force at an angle of more than 45°, the material is destroyed along the cleavage planes (the lowest strength of the pieces), which contributes to its destruction using less effort.

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