УДК 621.926

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DESTRUCTIVE EFFICIENCY OF GRINDING MEDIA IN HORIZONTAL PLANETARY MILL

The paper presents methods for calculating the destructive capacity of grinding media contained in a planetary mill, the main types of deformation such as compression, impact and abrasion. The results of calculation for one complete revolution drove at different angular speeds grinding drum. Found that the breaking strength of all types of loading exceeds the tensile strength of the material.

Introduction. Planetary mill is highly effective grinding device. Its research is being conducted in many countries by many scientists, including the authors of this work [1]. Its mechanics is studied and the basic modes of motion of grinding bodies in the grinding drum are established. The boundaries of the typical loading zones are determined. They are distributed in the form of a segment, offset relative to the carrier to a certain angle [2]. Within the segment, you can highlight areas of continuous motion, sliding and separation; each area is characterized by a predominant method having a most destructive effect on the material: smashing, abrasion and impact.

The influence of each of these methods on the grinding efficiency is estimated only indirectly, without calculation destruction failing stresses. Regarding these facts, the aim of this work is to measure the destructive effects of grinding bodies on the ground material.

The main part. The horizontal planetary mill with an external run was chosen as an object for analysis. As in most previously studied devices, the radius of the drum was assumed to ber = 0.1 m, geometric criterion k=r/R=0.5, the degree of loading – 50%.Since the experimental studies have shown that the highest efficiency is achieved with a centrifugal motion mode for loading, only this mode was subjected to analysis. Changing its grinding zones borders is shown in Fig.1. It is evident that for sustainable centrifugal mode, the basic zone is continuous motion, but sliding is typical closely to the center of the drum, and even separation of grinding bodies, followed by their fall.

Taking into account the fact that the failure stress in the planetary mill was not previously calculated, it was decided to establish its possible maximum value in characteristic points of the loading segment.

These are the points of continuous motion zone contacting the wall of the drum, and the points on the outer boundary of the other two zones. In the sliding and separation areas the failure stresses in destructive material were determined at only one point at the intersection of the boundary zone and a line drawn through the drum's center perpendicular to the carrier.

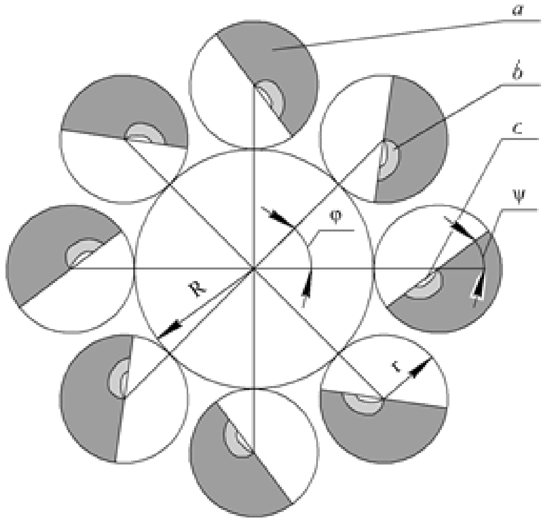


Fig.1. Changing grinding zones borders:
a – compression; *b* – impact; *c* – abrasion

Guided by the principle of achieving maximum stress as the main technological parameter, a maximum angular velocity of the drum was assumed to be ω = 180 rad/s. In order to compare the results, the calculations were performed for the angular velocity ω = 90 rad/s. Diameter of grinding media(steel balls) was assumed to bed = 18.5 mm, grinding material particles – 3 mm. Gypsum with compressive strength σ_{com} = 10 MPa was used in analytical studies as the grinding material. At the initial stage the prevailing compression impact zone was investigated. The pressure of grinding media on the particles material from the surface of the drum was calculated according to the previously proposed model [3], taking into account the interaction of grinding media:

$$F_{d_i} = 2 r_b^2 \rho \left(\omega^2 \frac{(r_i + r_b)^2 - r_0^2}{2} + (r_i + r_b - r_0) \times \left(\frac{\omega^2 k^2 R}{1+k} \cos(\psi - \varphi) - g \sin\psi \right) \right), \quad (1)$$

where r_b – grinding body radius, m; r_i –current radius, m; r_0 – zero radius, m; ρ – density of grinding material, kg/m^3;ω – angular velocity of the drum, rad/s; ψ, φ – current angle and the angle of the carrier rotation, respectively, degree.

Compressive stress calculations were performed at a fixed position of the drum rotation angle of the carrier φ = 45° (Fig. 1). At the same time their value was determined across the segment loading within terval sψ = 15°. The calculation results which are shown in Fig. 2, indicate that within the segments that load compressive stress changes cyclically. Thus, even in a fixed position the impact of the grinding media on the material is not static. It is natural, in each new position the force impact will change, and thus it ensures the destruction of non-stationary dynamic material.

The fact that the destruction would occur even under applied static load, shows the magnitude of compressive stress (Fig.2), which, when the angular velocity of the drum ω = 180 rad/s within the whole segment loading exceeds the tensile strength of gypsum stone in compression. With the decrease in the angular velocity to ω = 90 rad/s material degradation will occur only in some segment places where the peak stresses are marked.

Considering the dynamism of the process it can be stated that even with such an angular velocity, the material will be destroyed, although less efficiently. This, incidentally, is supported by experimental data [4].

To assess the impact force is much more complicated than that of the smashing one. Here it is necessary to determine the impact force of the grinding body on particle material and the area of their contact at the impact moment.

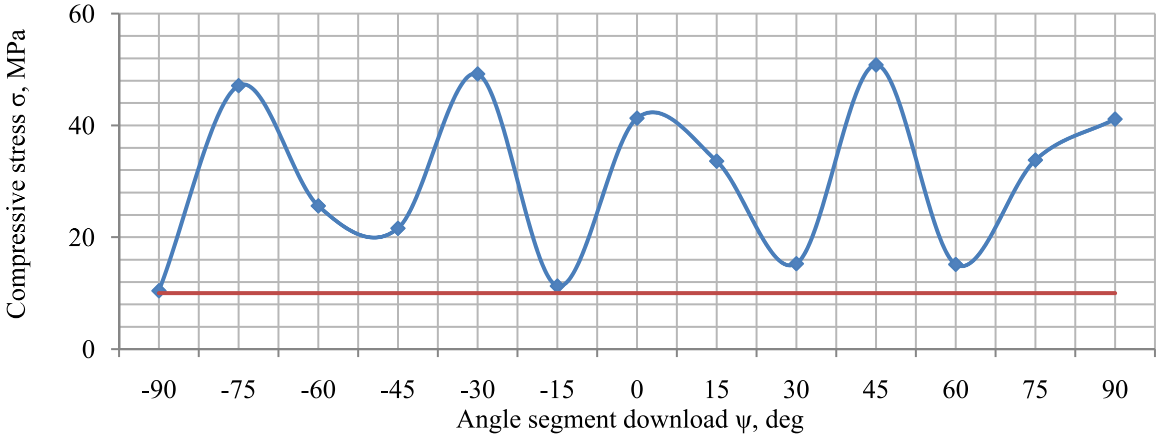
The impact force can be determined by the shock pulse:

$$m\upsilon = F_c t, \tag{2}$$

where m – mass of the grinding body, kg; υ – velocity of the body at the moment of impact, m/s; τ – the destruction time, sec.

Deformation time τ = 2L/c, where L – the characteristic size of degradable particles, m; c – speed of sound in a solid, m/s.

The impact velocity remains unknown. The speed of the grinding body after separation can be determined by transforming our developed method of calculating the height of its fall [5].



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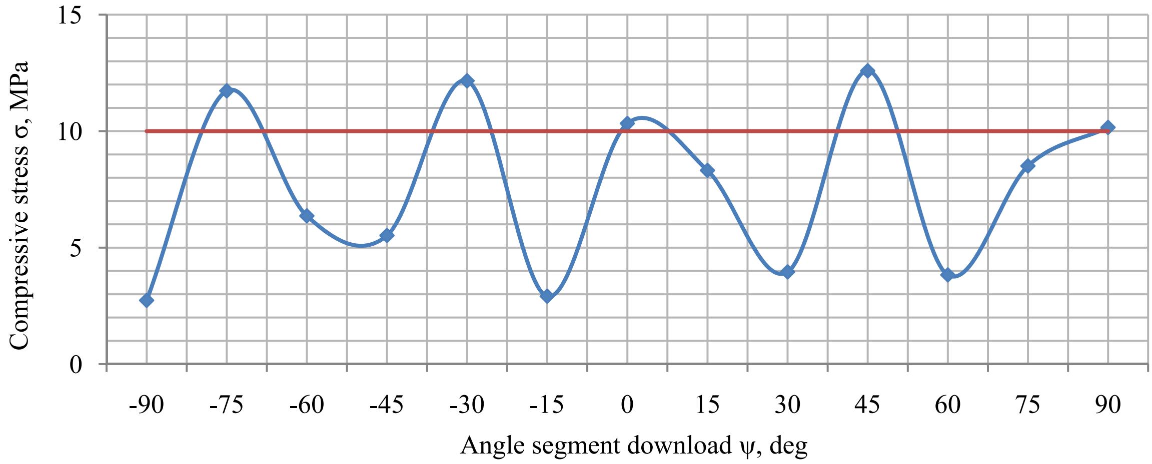


b

Fig.2. Change of compressive stresses in the segment loadings:
a – ω = 180 rad/s, φ = 45°; *b* – ω = 90 rad/s, φ=45°

The equations of motion of the grinding body along the curvilinear trajectories have the form:

$$x = R(1+k)\sin\varphi_0 + r\sin\psi_0 + \\ + \omega k R(\cos\varphi_0 + \cos\psi_0)t; \qquad (3)$$

$$y = -R(1+k)\cos\varphi_0 - r\cos\psi_0 + \\ + \omega k R(\sin\varphi_0 + \sin\psi_0)t - \frac{gt^2}{2}. \qquad (4)$$

Simultaneous solution of these equations with the circumference of the drum equation allows us to determine the coordinates of the first contact of grinding bodies with it and time of flight:

$$t = \frac{x - R(1+k)\sin\varphi_0 + r\sin\psi_0}{\omega k R(\cos\varphi_0 + \cos\psi_0)}. \qquad (5)$$

Having differentiated equations (3) and (4), we obtain the calculated curves to determine the components of velocity of grinding body along the curved path:

$$x' = \omega k R(\cos\varphi_0 + \cos\psi_0); \qquad (6)$$

$$y' = \omega k R(\sin\varphi_0 + \sin\psi_0) - gt. \qquad (7)$$

Substituting in equation (6) and (7) the value of the fall time, calculated by formula (5), we define the components x' and y' and the full speed during impact $\upsilon = \sqrt{(x')^2 + (y')^2}$.

To simplify the equation, we assume that the ground material at the moment of impact remains stationary, and a direct impact is implemented when the grinding body and a particle are in contact. The situation is, of course, somewhat idealized, but at the initial stage of the investigation it is quite acceptable, and, most importantly, this assumption makes possible immediately calculate the impact force F_c.

To determine the contact area we use a technique based on Hertz theory and tested by Sharapov [6].

The contact area is suggested to calculate by the formula:

$$S = 2\pi R_2^2 - \pi R_2 \times \\ \times \sqrt{4R_2^2 - R_2^2[(2R_1 - h)h]\frac{4R_1R_2 - 2R_1h + 4R_2^2 - 4R_2h + h^2}{R_2^2(R_1 + R_2 - h)^2}}, \qquad (8)$$

where R_1, R_2 – the radiuses of the sphere and of the material, respectively, m; h – depth of penetration of grinding body in the form of spherical grinding material, m.

The h value was calculated according to the formula:

$$h = \left(\frac{5m_1m_2(\upsilon_1 - \upsilon_2)^2\sqrt{R_1 + R_2}}{16(m_1 + m_2)\sqrt{R_1R_2}}\right)^{2/5} \times \\ \times \left(\frac{1 - \mu_1^2}{E_1} + \frac{1 - \mu_2^2}{E_2}\right)^{2/5}, \qquad (9)$$

where m_1, m_2 – are respectively the mass of the ball and the grinding particle, kg; E_1, E_2 – Young's modulus of the material and the grinding body; μ_1, μ_2 – Poisson coefficients for the ball and material; υ_1, υ_2 – speeds of the ball and material, respectively, m/s.

Another problematic issue is the determination of the ultimate strength of the material upon impact. We managed to establish the ratio of the compression strength ($\sigma_c = 1.2\sigma_{com}$) in directly from the works of Cherepanov [7].

Proposed algorithm for calculating the shock stress has been implemented for all eight positions of the grinding drum (Fig.3).

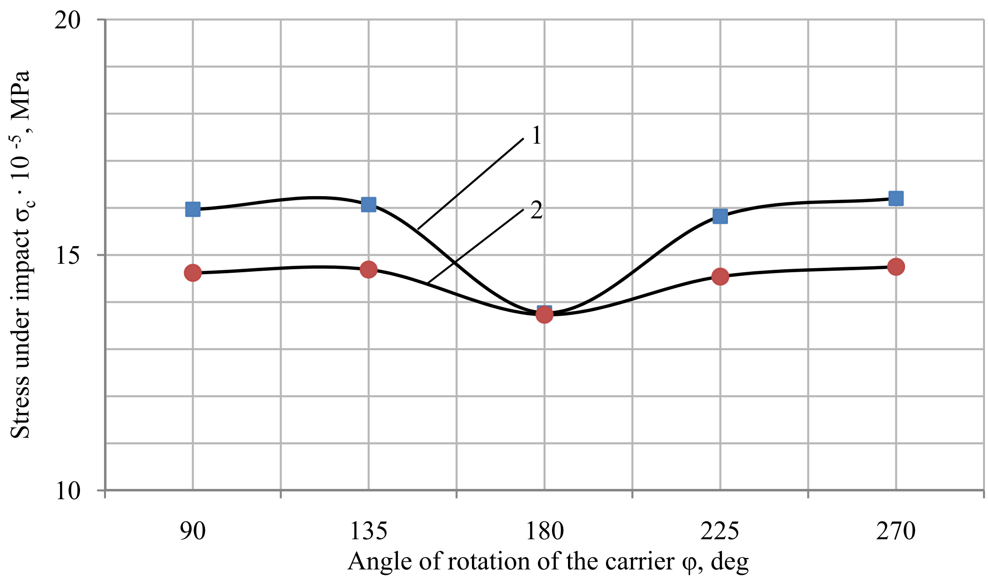


Fig.3. Changing the shock stress in one rotation of the carrier: 1 – ω = 180 rad/s; 2 – ω = 90 rad/s

Proposed algorithm for calculating the shock stress has been implemented for all eight positions of the grinding drum (Fig.3).

The calculated curves (Fig.3) show that the shock stresses are significantly higher than the compressive ones and exceed several times the tensile strength of the material for this kind of loading. More over, thechangeoftheangularvelocityfrom90 to 180 rad/s does not significantly affect the magnitude of stress.

An interesting fact is that the destruction effect manifests itself only in the range of angles of rotation of the carrierφ = 90– 270°. The explanation for this lies in the relative motion of the drum and grinding bodies in the other three positions φ = 315°; 0°; 45°. Here the drum rises up and catches a torn-off falling grinding body.

These assumptions are confirmed by calculation values of drop height of grinding bodies presented in [5]. This value tends to zero. Some reduction in stress shock at φ = 180°can be explained by decrease of impact on the trajectory of the falling grinding body by transferring inertial impact, directed horizontally along the carrier.

The authors came across with some difficulties when determining abrasive stresses. Abrading process of destruction is poorly studied, there are not any reliable and adequate physical and mathematical models.

Therefore, we use the one proposed by Hodakov, a leading specialist in grinding theory [8]. It is based on similar processes for grinding abrasive fracture (Fig. 4).

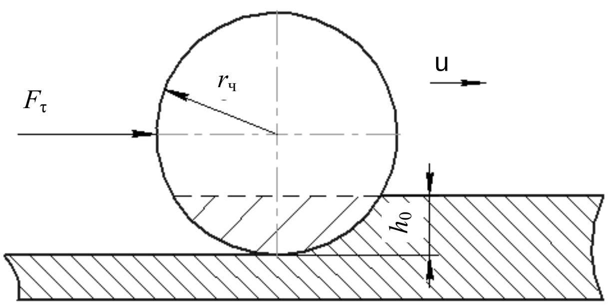


Fig.4. Design scheme of space segment definition

Assume that the grinding body by the pressure force is introduced into the material to a depth h_0 and under the influence of tangential efforts F_τ cuts the material layer.

Tangential force is determined from the conditions of sliding grinding bodies in the loading segment $F_t \geq fN$, where N – normal related reaction, f – coefficient of friction. The normal relation reaction is oppositely directed and equals to pressure force by module$|N| = |F_p|$, calculated by the formula (1).

Contact area S_c of the grinding body with material particle is a segment under abrasion, limited by ball radius r_b and the degree of penetration into the material h_0 (Fig. 4), and is calculated by the formula:

$$S_c = \frac{1}{2(r_ч l - c(r_ч - h_0))}, \tag{10}$$

where

$$c = 2\sqrt{h_0(2r_ч - h_0)}, \tag{11}$$

$$l = 0,01745 r_ч \alpha, \tag{12}$$

where α – is the angle, enclosed in the required segment, degree.

According to the Hertz theory, the degree of penetration into the material h_0 was determined by the equation:

$$h_0 = \left[\frac{3N(1-\mu^2)}{4E}\right]^{2/3} r_0^{-1/3}, \tag{13}$$

where μ – Poisson's ratio; E – elasticity module of the grinding material, MPa.

Tensile strength is according to Prandtl [8] $\tau_{ab} = \sigma_f/2$, where σ_f – fluidity limit, constituting 0.65 of tensile compression.

Results of calculation of abrasive impact are in the same eight positions of drums than that of stress impact; they are shown in Fig.5.

Here we may note a few features.

First, abrasive impacts can be compared to with shocking impacts, and they are significantly higher than compressive ones and shear strength.

Secondly, at the lower angular velocity ω = 90 rad/s abrasive stress has higher values and is characterized by a clear extremum at φ = 180°.

This fact is most likely due to a high mobility of moving grinding bodies (slipping velocity) due to the decrease of the pressure force.

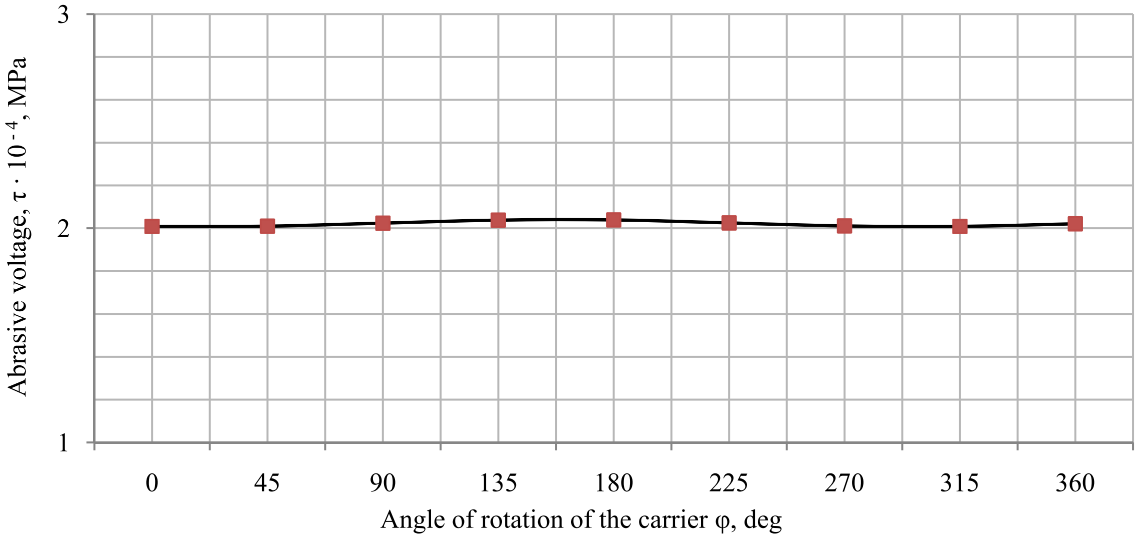
The peak stress value is shown at the moment when the transferring inertial force maximally enhances this mobility. With a significant increase of the angular velocity of the drum(up to 180rad/s) the grinding bodies sliding decreases.

The area with such movement is gradually transformed into a continuous one.

Therefore abrasive stresses decrease and stabilize in magnitude.

The obtained results can be considered the first step in the study of destructive impact of grinding bodies in a planetary mill. They require detailed analysis, additional calculations, and experimental verification.

You can not do snap judgements on the benefits of any impact of the method in terms of grinding efficiency. Despite the fact that the compressive stresses are much lower than the impact and abrasive stresses, their cyclical changes are substantially higher. In addition, the area of the continuous motion is much higher than the other two ones.



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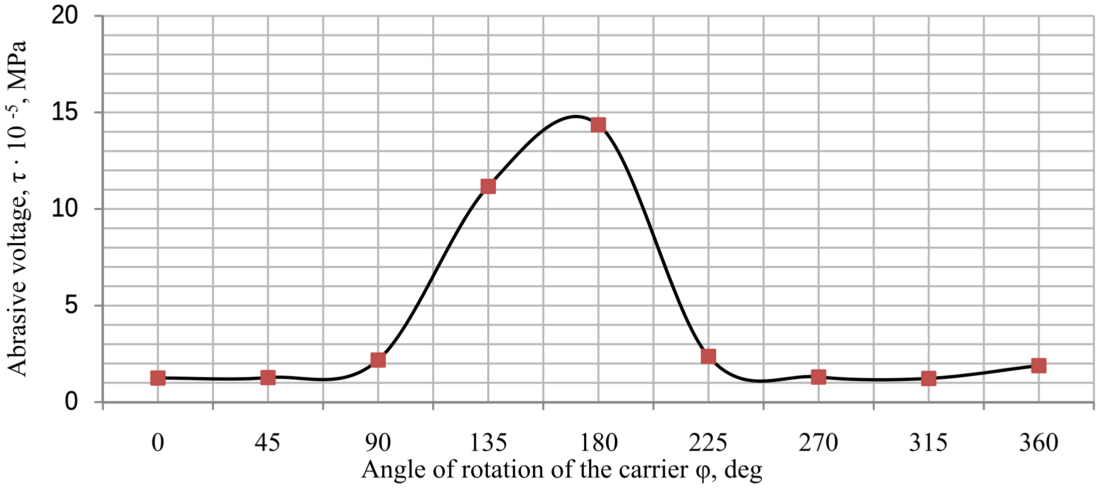

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Fig.5. Change of abrasive stress in one rotation of the carrier: *a* – ω = 180 rad/s; *b* – ω = 90 rad/s

Therefore, for an adequate assessment of each of the methods it is necessary to develop the research improving the physical and mathematical models of destructive materials in a planetary mill.

It is important to determine the ultimate strength of grinding materials under study at various loading. This complex of works is to be solved in future.

Conclusion. In this work, the attempt was made to link the mechanics of motion of grinding bodies with their destructive effect on the sample material.

The method and algorithm for calculating the destructive stresses at smashing, shocking and abrading influences are developed.

It is shown that for all types of loading destructive stress exceeds the tensile strength of the material.

The work can be considered an initial step in a new research of planetary mills. It has good prospects in both scientific and practical terms.

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Received 25.02.2013