ISSN 2306-8744
№ 1 (120)
2026
Вібрації в техніці та технологіях

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УДК 621.926.22-047.58
DOI: 10.37128/2306-8744-2026-1-7

NIP ANGLE OF A VIBRATORY JAW CRUSHER WITH AN INCLINED CRUSHING CHAMBER

The article examines the equilibrium conditions of a material piece during its clamping between the jaws of a vibrating jaw crusher with an inclined crushing chamber. The crusher design includes a body mounted on elastic elements, featuring a rigidly connected inclined lower jaw and a hinged upper jaw, which together define the nip angle. The physical picture of the jaw-material interaction, obtained via high-speed imaging, demonstrates a stable position of the piece on the transporting surface of the jaw during the clamping phase, which is characteristic of this process.

Dynamic processes during the clamping period were investigated using a vibration-measuring system equipped with displacement and acceleration sensors, a magneto-induction tachometer, and an oscilloscope. The study determined the contact time between the jaw working surfaces and the material, the vibration amplitude, and the acceleration of the upper jaw. Experimental oscillograms characterize the dynamics in the contact zone with a non-crushable object and during jaw wedging.

Analysis of the oscillograms reveals that during the entire clamping period, the upper jaw is subjected to a high-frequency alternating force directed perpendicularly to its working surface. This result justifies the application of an effective friction coefficient for determining the nip angle. A mathematical model has been developed to establish the limiting nip angle for inclined crushing chambers, accounting for inertial forces and the effective friction coefficient.

The obtained results provide a basis for designing advanced crushing chambers and optimizing the production of fine-grained materials.

Keywords: *Vibrating jaw crusher, inclined crushing chamber, nip angle, effective friction coefficient*

Problem statement. Crushing and grinding operations are the most energy-intensive in the overall production process of processing various materials, consuming about 20% of the electricity produced worldwide [5]. This multi-stage technological process employs a variety of crushers and mills to reduce raw materials from an initial size exceeding 1000 mm down to a fine powder.

Thanks to its relatively simple design and operating principle, the jaw crusher, invented in the mid-19th century by American Ely Withney Blake [1] as a machine for crushing stone, has found wide application in virtually all industries. It consisted of a vertically positioned fixed jaw and a movable jaw fixed at an angle to the suspension axis, which was driven by a crank-and-connecting rod mechanism. Subsequently, significant changes were made to the crusher design. Many variants of kinematic schemes determining the nature of the movable jaw's movement appeared, crusher designs with complex jaw movement and two movable jaws were developed, and a large number of developments were devoted to protective devices and the profile of lining plates [3, 4, 9, 10]. However, the basic principles implemented in the first crusher models remained unchanged. Materials are crushed by crushing a piece between the jaws [2] as it is moved to the discharge window in a vertically positioned crushing chamber. Despite the simplicity of the design and operating principle, this class of crushers has a number of significant drawbacks: low crushing efficiency, low frequency of impact on the material during crushing, heavy weight, strong vibrations during operation, etc. In addition, the use of jaw crushers with simple and complex swinging movable jaws to obtain fine-grained materials is irrational due to the insignificant yield of the finished product. Crushers have a small number of control parameters that affect the technological indicators of the disintegration of the processed material. One of these primary non-adjustable parameters is the nip angle, formed by the working surfaces of the crushing jaws. The nip angle between the swing and stationary jaws affects both the comminution intensity and the overall dimensions of the crusher; this necessitates determining a rational nip angle value that ensures the reliable retention of the material within the crushing chamber at the initial moment of engagement between the jaws.

In most sources [6, 5], the determination of the maximum nip angle, which excludes the possibility of a piece being pushed out of the loading opening of the crushing chamber, is based on the equilibrium of the piece of material at the moment it is clamped between the jaws of the crusher. The interaction process is represented as follows. A piece that enters the crushing chamber when moved to the discharge slot encounters the working surfaces of the crushing jaws. At the moment of contact, the piece may be pushed upward into the loading zone or remain in a clamped state. The main factors of equilibrium are the holding force (friction) and the pushing force. This approach determines the limiting value of the nip angle $\alpha = 2\rho$, where ρ is the angle of sliding friction.

Jaw crushers have been further developed by increasing the frequency of vibration of the crushing jaws, moving from a static to a dynamic method of material destruction. A new class of machines has been created based on this principle – vibrating jaw crushers [7]. In general terms, the design of a vibrating jaw crusher is an oscillating system in which the jaws are subjected to vibrations with a frequency of 16–32 Hz [8].

Despite significant differences in how the jaws interact with the material, the nip angle is determined using conventional methods and is typically set to not exceed double the friction angle. However, a somewhat different interaction between the material particles and the crushing jaws occurs in a vibratory jaw crusher with an inclined crushing chamber.

The purpose of the research is to substantiate the limiting nip angle for a vibratory jaw crusher with an inclined crushing chamber, considering the effective friction coefficient.

Presentation of the main material. The vibrating jaw crusher with an inclined crushing chamber (Fig. 1) comprises a housing 1 mounted on vibration-isolating support shock absorbers 2. The lower jaw 3 is rigidly connected to the housing, while the upper jaw 4 is rotatably mounted in the housing uprights by means of a suspension axle 5. The lower and upper jaws are connected by a flexible element 6, and each of them is equipped with lining plates 7. The vibrations of the jaws are generated by a twin-shaft inertial vibration exciter 8. The suspension axle is connected to the upper jaw by means of a bearing 9.

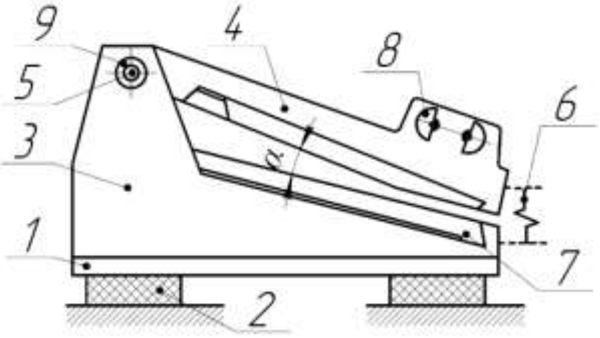
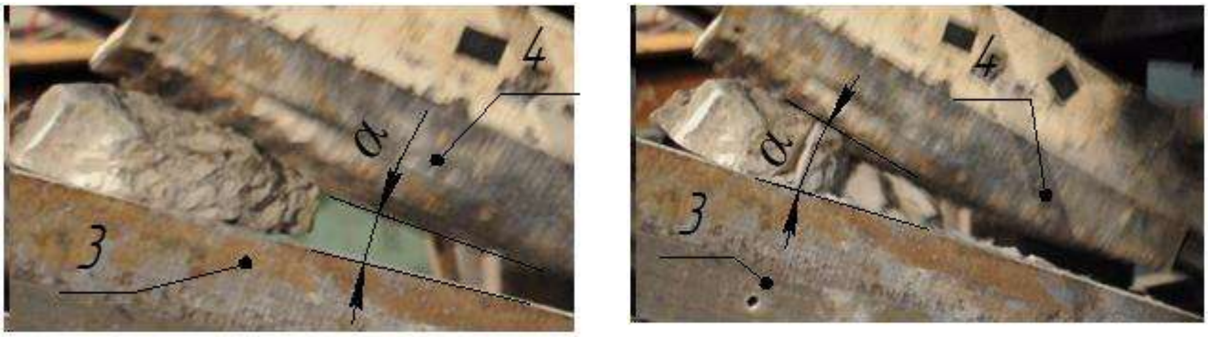


Fig. 1. Structural diagram of the crusher

The vibrating jaw crusher operates as follows. Under the action of the exciting force of the vibrator 8, jaw 3 and jaw 4 perform oscillatory movements. The amplitude of the oscillations of the upper jaw 4 is significantly higher than the amplitude of the oscillations of jaw 3. The oscillations of the lower jaw 3 transport the material to the discharge, while the oscillations of the upper jaw 4 crush it. The raw material entering the crusher's feed opening is transported to the discharge slot along the lower jaw 3 and, upon contact with the working surface of the upper jaw 4, is subjected to high-frequency impact loading. The material is crushed in the crushing chamber formed by the working surfaces of the jaws and having a nip angle α.

The interaction between the piece and the upper jaw was recorded by a high-speed camera.

The flow of material entering the loading zone from the feeder is a loose mass of randomly arranged pieces. Large pieces self-orient and assume a stable transport position. There is no gap between the jaws surfaces and the piece; it is in a clamped position (Fig. 2a). As the jaws continue to close, the piece begins to break down. Two forms of material state appear: a stationary state, corresponding to a clamped, already partially destroyed piece in the upper part of the crushing zone, and a mobile state, corresponding to crushed material moving freely to the discharge window of the crusher (Fig. 2b).



a b

Fig. 2 Piece of material in the crushing chamber: a – initial moment of gripping the piece by the jaws; b – start of the piece destruction process

The calculation model, which incorporates the inertial forces acting on the clamped material during transport, is shown in Fig. 3.

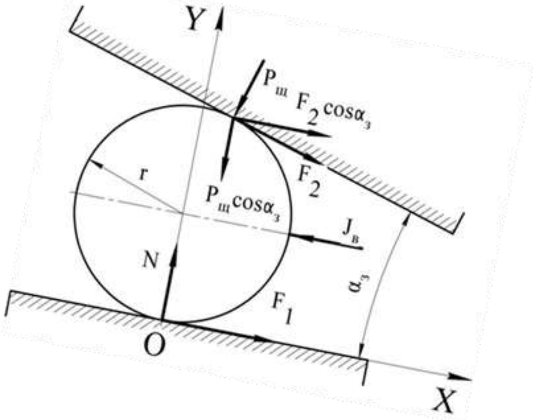


Fig. 3. **Calculation model for determining the nip angle*: Pщ* - force acting on the piece from the upper jaw; *N* - reaction of the support surface (passive jaw of the crusher); *F₁* - friction force between the piece and the lower jaw; *F₂* - friction force between the piece and the upper jaw; *α₃* – nip angle; *r* - radius of the piece being crushed; *Jв* - inertial force pushing the piece out.**

$$\Sigma X = F_1 + F_2 \cos\alpha_з - P_щ \sin\alpha_з - J_в = 0 \qquad (1)$$
$$\Sigma Y = N - P_щ \cos\alpha_з - F_2 \sin\alpha_з = 0$$

Where:

Jв - the inertial force ejecting the material piece.

Taking into account the coefficient of sliding friction *f,* equations (1) take the following form:

$$fN + fP_щ \cos\alpha_з - P_щ \sin\alpha_з - J_в = 0 \qquad (2)$$
$$N - P_щ \cos\alpha_з - fP_щ \sin\alpha_з = 0$$

After performing the appropriate transformations, we obtain:

$$2P_щ f \cos\alpha_з - P_щ \sin\alpha_з (1 - f^2) - J_в = 0$$
$$\tan\alpha_з = \frac{2f}{1 - f^2} - \frac{J_в}{P_щ (1 - f^2)} \qquad (3)$$

The second term of expression (3) determines the decrease in the limiting nip angle compared to the static application of the load.

Given that *f = tan ρ*, we obtain:

$$\tan\alpha_з = \frac{2\tan\rho}{1 - \tan\rho^2} - \frac{J_в}{P_щ (1 - \tan\rho^2)} \qquad (4)$$

Research was conducted on a laboratory crusher prototype to study the interaction between the jaws and a material piece. The experimental setup included: a BI6-6TH vibration measurement system equipped with displacement and acceleration sensors, a TMI magnetic induction tachometer, a 5-channel USB oscilloscope, and a Samsung RV520 laptop. Figure 4 illustrates the sensor layout on the experimental prototype and the data acquisition system.

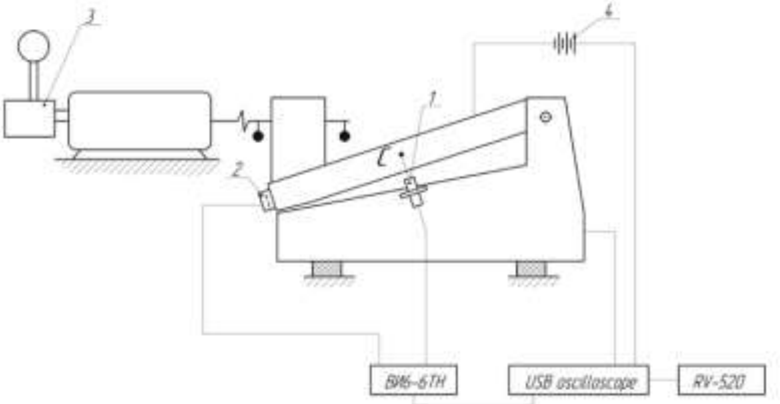


Fig. 4. Measurement setup for monitoring the motion parameters of crusher components

The motion parameters of the upper jaw relative to the lower jaw were determined using a ДП-3см type displacement sensor 1 with a measurement range of ±*20 mm*. The sensor body is rigidly attached to the lower jaw, while its plunger is fixed to the upper jaw at point C. Through established geometric relationships, the measured displacement values of point C are converted into the relative angular movement of the upper jaw, allowing for the subsequent calculation of kinematic characteristics for any point on its surface. Acceleration sensor 2 was used to measure the absolute acceleration of either the upper or lower jaw. Based on the readings from the magnetic induction tachometer 3, the required rotation speed of the vibration exciter's unbalance shafts is preset for the experiment.

During the research, the contact time between the jaw working surfaces and the material was determined as it passed through the crushing chamber. For this purpose, one terminal of the battery (4) (conventionally defined as positive) was connected directly to the input jack of the USB oscilloscope, while the second terminal (negative) of the battery was attached to the upper jaw. The negative input of the oscilloscope jack was connected to the lower jaw.

The circuit is operational when a gap (corresponding to the discharge setting) exists between the jaw working surfaces in the static equilibrium position, ensuring the electrical circuit remains open. Additionally, the upper jaw must be electrically insulated from all other conductive components of the crusher.

The upper jaw is electrically isolated from the lower jaw by means of textolite sliding bearings 9 (Fig. 1), which are installed instead of rolling bearings on the jaw suspension axis, as well as rubber-metal elastic elements 6 (Fig. 1), located between the upper and lower jaws of the crusher. The swing jaw is electrically isolated from the electric motor by a flexible diaphragm coupling, while displacement sensor 1 (Fig. 4) is attached to the upper and lower jaws of the crusher via textolite plates. To obtain raw data on the interaction process between the material and the jaw working surfaces, conductive elements are fed into the crushing chamber. At the moment of contact between a conductive element and the jaw surfaces (the initial phase of impact), the electrical circuit is closed, sending a signal to the recording equipment.

The experimental studies yielded oscillograms (Fig. 5) characterizing the interaction between the jaws and the material piece during the clamping phase. Figure 5a shows an oscillogram of the interaction between the upper jaw and a non-crushable object (low-carbon ferrochrome). The upward shift in the lower value of the oscillation amplitude (pos. 1) is caused by the movement of the non-crushable object to the unloading window and the separation of the jaws. The contact between the jaws and the non-crushable object is reflected by the curve (Fig. 5.a; pos. 3), in which the upper horizontal sections determine the interval and time of clamping the material.

Since the acceleration sensor is mounted on the upper jaw, the curve (Fig. 5, a; pos. 2) characterizes the absolute vertical acceleration of the upper jaw. The error introduced by the vibrations of the lower jaw was accounted for using the oscillogram (Fig. 5, b) of the crusher's operation while the jaws were wedged by a non-crushable object. The segment highlighted by vertical lines (Fig. 5, b; pos. 3) defines the boundary of contact loss between the jaw and the material. The subsequent interval represents the full clamping of the material (indicated by the straight line) and the acceleration (Fig. 5, b; pos. 2) resulting from the lower jaw's vibrations. The insignificant magnitude of these vibrations practically does not affect the value or the nature of the accelerations recorded by the upper jaw sensor.

Analysis of the oscillogram segment highlighted by vertical lines (Fig. 5, a) revealed the processes occurring in the contact zone between the upper jaw and the material. The trace representing the jaw-material contact is continuous, indicating that the material remains in a clamped state under the force $P_{Щ}$ throughout the entire interval. Throughout the entire material clamping period, the upper jaw is subjected to high-frequency alternating acceleration. Consequently, in addition to the force $P_{Щ}$, an alternating force acts on the clamped material piece, directed perpendicularly to the working surface of the upper jaw.

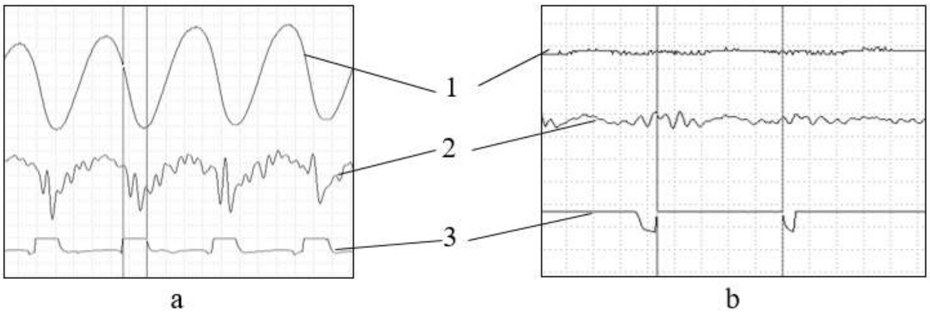


Fig. 5. Oscillograms of the interaction between the jaws and the material: **a - dynamic processes in the contact zone with a non-crushable object; b - dynamic processes in the contact zone during jaw wedging; 1 - vibration amplitude (displacement) of the upper jaw; 2 - acceleration of the upper jaw; 3 - recording of the jaw-material contact.**

The obtained result justifies the use of an effective friction coefficient when determining the nip angle of the crusher, as substantiated in [11, 12]; the value of this coefficient is determined according to the following expression:

$$f^{*} = f\left(1 - \frac{\Phi}{N}\right), \qquad (5)$$

where: f^{*} - effective friction coefficient; Φ - alternating force.

Then, the nip angle of the crusher is determined as:

$$\alpha_{з} = \operatorname{arc\,tan}\left(\frac{2\,f^{*}}{1 - f^{*2}} - \frac{J_{в}}{P_{щ}\left(1 - f^{*2}\right)}\right) \qquad (6)$$

The resulting analytical expression determines the nip angle, accounting for the dynamic processes in the material-jaw contact zone that are characteristic of a crusher with an inclined working chamber.

Conclusions. Research indicates that a defining characteristic of a crusher with an inclined working chamber is the occurrence of operating modes where inertial forces act to eject the material during clamping. This alternating force during the clamping phase is a unique feature of vibrating crushers with inclined chambers. Furthermore, the maximum nip angle in such designs is inherently smaller than in conventional jaw crushers, necessitating the development of specialized crushing chamber geometries.

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КУТ ЗАХОПЛЕННЯ ВІБРАЦІЙНОЇ ЩОКОВОЇ ДРОБАРКИ З ПОХИЛОЮ КАМЕРОЮ ДРОБЛЕННЯ

У статті розглянуто умови рівноваги куска матеріалу в момент його затиснення між щоками вібраційної дробарки з похилою камерою подрібнення. Конструкція апарату включає корпус на пружних елементах із жорстко закріпленою нижньою та шарнірно підвішеною верхньою щоками, що формують кут захоплення. Отримана методом швидкісної зйомки фізична картина взаємодії показує характерне для цього процесу стійке положення куска на транспортувальній поверхні щоки в момент затиснення.

Динамічні процеси досліджено за допомогою вібровимірювального комплексу з датчиками переміщення, прискорення та магнітоіндукційним тахометром. Визначено час контакту робочих поверхонь із *матеріалом, розмах коливань та прискорення верхньої щоки. Експериментальні осцилограми описують динаміку в зоні контакту з недробимим тілом та при розклинюванні щік.*

Аналіз підтвердив, що під час затиснення на верхню щоку діє високочастотна знакозмінна сила, спрямована перпендикулярно до її поверхні. Це дозволяє використовувати ефективний коефіцієнт тертя при розрахунках. Розроблено математичну модель та отримано аналітичні залежності для визначення граничного кута захоплення з урахуванням інерційних сил та ефективного тертя.

Результати дослідження є базою для проектування нових камер подрібнення та вдосконалення технологій отримання дрібнозернистих матеріалів.

Keywords: *вібраційна щокова дробарка, похила камера дроблення, кут затискання, ефективний коефіцієнт тертя.*

Відомості про автора

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Стаття надійшла 16.03.2026
Стаття прийнята 23.03.2026
Опубліковано 17.04.2026