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ANALYSIS OF THE ENERGY LAWS OF MATERIAL DESTRUCTION

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The paper provides an analysis of the latest research in the field of material destruction processes, on the basis of which it was established that modern methods of determining the energy of material destruction differ significantly from each other, are based on different energy hypotheses, both according to accepted assumptions and according to the obtained results. Thus, the lack of a generally accepted model of the grinding process and a single method of determining the energy consumption of the process of destruction of materials by crushing machines is the problem that needs to be solved. For this purpose, an analysis of the main classical laws of destruction of materials in the crushing chamber was carried out.

Keywords: energy of destruction, crusher, proportionality factor, work index, rocks, shock loads, degree of crushing, sieve size.

Introduction. The most common materials in industrial construction are concrete, reinforced concrete, bricks, mortars, etc. A wide range of technological equipment is used for the production of these building materials. The processes of crushing, screening and grinding are the largest in terms of the volume of work and energy consumption in the production of building materials. Crushing and sorting and grinding equipment are used to perform these processes. An important place among such equipment is occupied by crushers and mills, since crushing and grinding processes are characterized by significant energy and operating costs. Rock or secondary raw materials can be used for the production of building materials. The use of secondary raw materials as a source of building materials is becoming widespread and is the basis of recycling processes and zero-waste production. In most cases, the raw materials that come from the quarry or from the construction site are not suitable for use in construction. That is, it must be processed. Technological processing includes the following operations: preliminary sorting, crushing, sorting of crushing products into specified fractions, washing, transportation and storage of finished products. Among the listed processes, the crushing process is the largest in terms of energy consumption. The process of crushing is the process of reducing the size of the material under the condition of applying an external load, as a result of which the material is divided into parts and the individual parts acquire a more rounded shape. When considering the process of destruction in the crushing chamber of the crusher, the following main parameters of the material should be taken into account: physical properties, quantity, methods of preliminary treatment, dimensions of the crushing chamber, the method of applying the load, the shape of the crushing surface, etc. That is, the number of parameters that determine the destruction process is large. Most of the theories that describe the energy consumption of the destruction process are based on empirical indicators and are not supported by the theoretical foundations of the process. Thus, the research of the energy parameters of the crushing process and the creation of a theoretically justified method of determining the energy consumption for most crushing machines is an urgent task.

Analysis of publications. The study of the energy of destruction of a mountain massif based on the improved Griffiths dependence is considered in works [1], [2]. The dependence on the determination of the fracture energy contains the parameter of the critical length of the crack and the adjusted parameter of the specific surface energy based on the regression analysis of the experimental data. This dependence is somewhat difficult to use, as it includes the critical length of the crack and the specific surface energy, the determination of which is not a simple task. On the other hand, this dependence is suitable for use when considering the problem of destruction only on the plane. In the source [3], the author claims that crack growth and material destruction occurs along shear lines, i.e. contact friction forces play a key role in destruction. However, the use of these dependencies to optimize the crushing process is complicated as they include the geometric characteristics of the crack. In addition, shock loads should be taken into account under conditions of vibration on the material [4]. When shock loads are applied, cracks in the material occur as a result of the passage of the shock wave. In this case, tangential stresses may not play a key role in crack propagation. In work [5], it is proposed to determine the energy of destruction based on the dependence of J. Svensen and J. Murkes, which is built on the hypothesis of F. Bond. Correlating the dependence of J. Svensen and J. Murkes with the consumption of electricity, the author derives the parameter of constant current strength, which is necessary to reduce the size of the collapsing particle. As is well known, Bond's hypothesis is best suited to describe the crushing process in the medium particle size range. Thus, the description of the crushing process in [5] is given for a narrow range of crushing machines. The classical hypothesis of energy consumption for the destruction process (hypothesis of volumes) is considered in [6], which is also suitable for describing energy consumption for a certain range of crushing machines. In work [7], the dynamic destruction of the material in a vibrating jaw crusher is investigated. To determine the specific energy consumption, a dependence is used, which is built on a combination of the theory of volumes and the theory of surfaces. A brittle material, such as sandstone, and a plastic material, such as talc, are used as the working body. This work is based on energy hypotheses that do not take into account the presence of a crack in the material, and the destruction process itself is considered as a single process. In work [8], it is proposed to determine the energy of destruction of the material in the crushing chamber on the basis of direct measurement of the engine power during the operation of the crusher. This method is based on statistical data and can be applied as an average indicator of energy consumption for a specific type of machine. In [9] it is proposed to determine the energy spent on the crushing process using the adaptive neuron-fuzzy interference system ANFIS. This system is a system of predictive calculations, and is built on the basis of an adaptive neural network. This direction of research is promising in the field of optimizing the operation of crushing equipment, but it requires a more in-depth study of the neural network. On the other hand, the ANFIS method of predicted calculations does not explain the basic laws of the physics of the destruction process, but accepts the relevant statistical parameters as input, then processes these parameters with the help of empirical dependencies and produces a result for further adjustment of the work process. The above-mentioned methods of determining the energy of destruction of a material are significantly different from each other, based on different energy hypotheses, both according to the accepted assumptions and according to the obtained results. Thus, the lack of a generally accepted model of the grinding process and a single method of determining the energy consumption of the process of destruction of materials by crushing machines is the problem that needs to be solved.

Purpose of the paper. The purpose of the study is to analyze the main energy laws of the crushing process. In order to achieve this goal, the following tasks were solved: 1) review of the latest research on the energy costs of the crushing process and establishment of dependencies that most fully describe the process and are based on the physics of the destruction process; 2) study of changes in the parameters of energy laws and their impact on energy costs; 3) analysis of the obtained data and presentation of conclusions regarding further research.

Research results. All existing energy laws that describe the process of destruction in the crushing chamber of crushing machines can be conditionally divided into two groups. The first group is the basic laws and the second group is the energy laws that complement or specify the laws from the first group.

The first group of energy laws includes the following: 1) Rittinger's law (hypothesis of surfaces); 2) the Kirpichev-Kick law (volume hypothesis); 3) Bond's law; 4) Rebinder's law. The fourth law is a variation of the first two. Let's analyze these laws in more detail.

Rittinger's first law states that the energy of destruction of a material is proportional to the newly formed surface. This law is written as follows:

$$A_{rit} = K_{rit} S , \tag{1}$$

where K_{rit} – the coefficient of proportionality established experimentally, J/m^2;S – the size of the newly formed surface, m^2.

When analyzing this dependence, the determination of the value of the newly formed surface S and the determination of the proportionality factor are somewhat difficult K_{rit}.

When crushing a cubic piece of size D with a defined degree of crushing, the size of the newly formed surface will be equal to[10], [11], [12]:

$$S = 6(D/i)^2 \cdot \left(D^3 / (D/i)^3\right) - 6D^2 = 6D^2(i-1), \tag{2}$$

where D/I- the size of the cubic piece of the crushed product; $D^3/(D/i)^3$ - the number of cubic pieces formed during crushing from the original piece; i – degree of crushing.

Then the work of grinding one piece will be equal to [2], [10], [13]:

$$A_{rit}=K_{rit}\times S=6K_{rit}(i-1)D^2. \tag{3}$$

For further research, for the sake of simplification, we will take the shape of the body of destruction in the form of a cube. Then, according to Rittinger's theory, the total destruction energy should be equal:

$$A_{\Sigma rit}=3A_{rit}=18K_{rit}(i-1)D^2\,. \tag{4}$$

In the source [14] it is noted that the value of specific crushing energy for jaw crushers is within 0.828-1.98 kJ/kg. This value is obtained during the crushing of igneous rocks, namely granite, diabase, metabasalt. For sedimentary rocks (siltstone), the specific energy of destruction is approximately equal to 1.26 kJ/kg.

In the source [15], studies were conducted to determine the specific energy of destruction of limestone rocks, which was 1.012-3.298 kJ/kg. In the source [16], based on research, it is noted that the specific energy of destruction of granite is equal to 1.5 kJ/kg, and for limestone it is approximately 1 kJ/kg. These researches give us practical values of specific energy consumption limits for jaw crushers when destroying the corresponding rocks. It is also noted in source [16] that the Bond theory for determining the energy of destruction is not accurate when destroying a single spherical body in the crushing chamber of a jaw crusher.

In the source [17] it was determined that the energy of diabase destruction in the crushing chamber of the jaw crusher lies within 2.56-4.09 kJ/kg. For sedimentary rocks, the specific energy of destruction is 1.16-1.93 kJ/kg. However, it should be noted that the energy in work [17] was measured directly on the motor shaft. In the previously reviewed works, the energy of crushing was determined either in the crushing chamber of the crusher or with the help of special tests for destruction.

In order to study the energy consumption in the crushing process, we will list the necessary technical characteristics of the most common sizes of crushing machines in Table 1.

In the last column of Table 1, we enter the calculated specific energy consumption of the crushing process on the motor shaft when crushing granite with a density within 2600 kg/m^3 and a strength of up to 250 MPa. As we can see from the data in the table, the energy consumption for jaw crushers does not significantly deviate from the presented values for granite in the source [14]. On the basis of these data, we can plot graphs of the dependence of energy consumption on the area of the newly formed surface and determine the limits of the Rittinger coefficient change. The size of the material is taken accordingly for each class of crushers presented in Table 1.

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Table 1

Technical characteristics of crushing machines

Crusher standard size	Degree of crushing, i	The size of the finished product d, mm	Maximum performance Q, m^3/hour	Maximum power P_{max}, kW	Specific energy intensity of the crushing process $E_{пит}$, (kJ/kg)*hour
Double Toggle Jaw Crusher					
900x1200	5.7	130	180	90	0.69
1200x1500	6.45	155	310	160	0.71
1500x2100	7.2	180	600	250	0.58
C200(Metso)	4	300	1538.75	400	0.36
C160(Metso)	3.2	300	1193.13	250	0.29
C130(Metso)	3.2	250	791.8	185	0.32
Single Toggle Jaw Crusher					
250x400	2.62	40	8	17	2.3
400x900	3.4	60	35	45	1.64
600x900	2.55	100	75	75	0.67
C96(Metso)	2.62	175	370	90	0.34
C80(Metso)	2.47	175	321.25	75	0.32
CJ211(Sandvik)	3.15	200	306.25	90	0.41
CJ411(Sandvik)	3.33	225	353.12	110	0.43
CJ612(Sandvik)	3.6	275	503.125	160	0.44
CJ815(Sandvik)	3.9	300	725	200	0.38
Gyratory Cone Crusher					
900/140	5.35	140	420	250	0.82
1200/150	6.67	150	680	320	0.65
1500/180	6.67	300	1450	400	0.38
GP500S(Metso)	6.67	75	625	315	0.69
CS660(Sandvik)	8	70	656	315	0.66
CS440(Sandvik)	10	41	320	220	0.95
G150(Kubria)	9	56	312,5	315	1,39
Cone Crushers Type Symons					
1200	9.25	20	77	75	1.22
1750	10	25	170	160	1.84
2200	11,67	30	360	250	1.14
HP500(Metso)	11	51	494	355	0.99
HP800(Metso)	11	51	750	600	1.1
Vibrating Jaw Crushers					
440x800	8,75	40	22	30	1.88
600x800	7,14	70	47	60	1.76
1200x1500	10	100	187,5	110	0.81

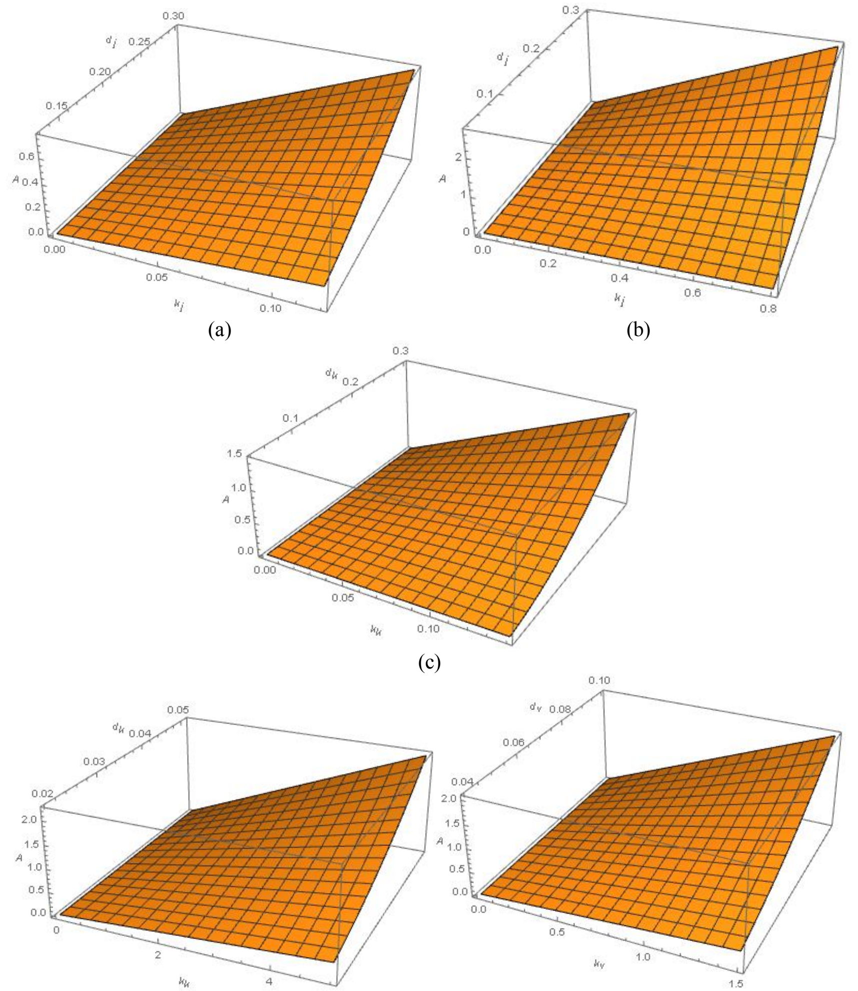

Fig. 1. Graphs of the dependence of the proportionality coefficient according to Rittinger's theory on the consumed energy: (a) – Double Toggle Jaw Crusher; (b) – Single Toggle Jaw Crusher; (c) – Gyratory Cone Crusher; (d) – Cone Crushers Type Symons; (e) - Vibrating Jaw Crushers

Knowing the specific energy intensity of the crushing process and the dimensions of the starting material, it is possible to determine the range of change of the proportionality factor for the corresponding class of machines.

For convenience, the range of changes in the proportionality coefficient according to Rittinger's theory for each class of machines is listed in Table 2.

Table 2

Proportionality coefficients for the relevant classes of machines

Types of Crushing Machines	The Average Value of the Degree of Crushing,i	Coefficients of proportionality		
		Rittinger, K_r	Kirpicheva -Kika, K_{kk}	Law of the Rodina, $K_в$
Double Toggle Jaw Crusher	4,96	0…0,12	0…28	9…18
Single Toggle Jaw Crusher	3,07	0…0,8	0…90	5…10
Gyratory Cone Crusher	7,48	0…0,14	0…50	6,8…14
Cone Crushers Type Symons	10,58	0…5	0…15000	5,9…12
Vibrating Jaw Crushers	8,63	0…1,5	0…2000	5,8…12

Based on the obtained range of values for the proportionality coefficient according to Rittinger, the following conclusions can be drawn. For most crushing machines from the accepted sample, the Rittinger coefficient varies from 0 to 1. And only in Cone Crushers Type Symons and Vibrating Jaw Crushers, the Rittinger coefficient varies from 0 to 5. Crushers in which the Rittinger coefficient can take values greater than 1 are used in stages of shallow crushing and have relatively significant degrees of crushing. This confirms the fact that for smaller fractions of the material, a larger amount of energy must be spent. Classically, most scientific sources claim that Rittinger's law is most suitable for determining energy consumption during fine grinding. It should be noted that the physical properties of the material, the costs of friction in machine nodes, heat losses, the amount of material in the crushing chamber, etc., must be taken into account in the energy costs for material destruction. All these parameters in the Rittinger dependence must be taken into account by the proportionality factor. However, in most cases, this coefficient is determined by an experimental method and does not have a calculation method.

Consider the following approach, which is based on the determination of the fracture energy using the Kirpichev-Kick law or the volume hypothesis. According to the volume hypothesis [10], [13], the A_V energy required for the same change in shape of geometrically similar and homogeneous bodies varies in proportion to the volumes or weights of these bodies. The dependency itself has the following form:

$$A_V = K_V D_0^3 = \frac{\sigma_{ст}^2 V}{2E}, \tag{5}$$

where K_V– empirical coefficient of proportionality, J/m3; V – the volume of a cubic piece with an edge D_0; $\sigma_{ст}$ – stress arising during deformation of the crushed body (compressive strength limit of the material), N/m^2; E– Young's modulus, N/m^2.

Let's build graphs to determine the range of change of the proportionality coefficient according to the Kirpichev-Kick theory, Fig. 2.

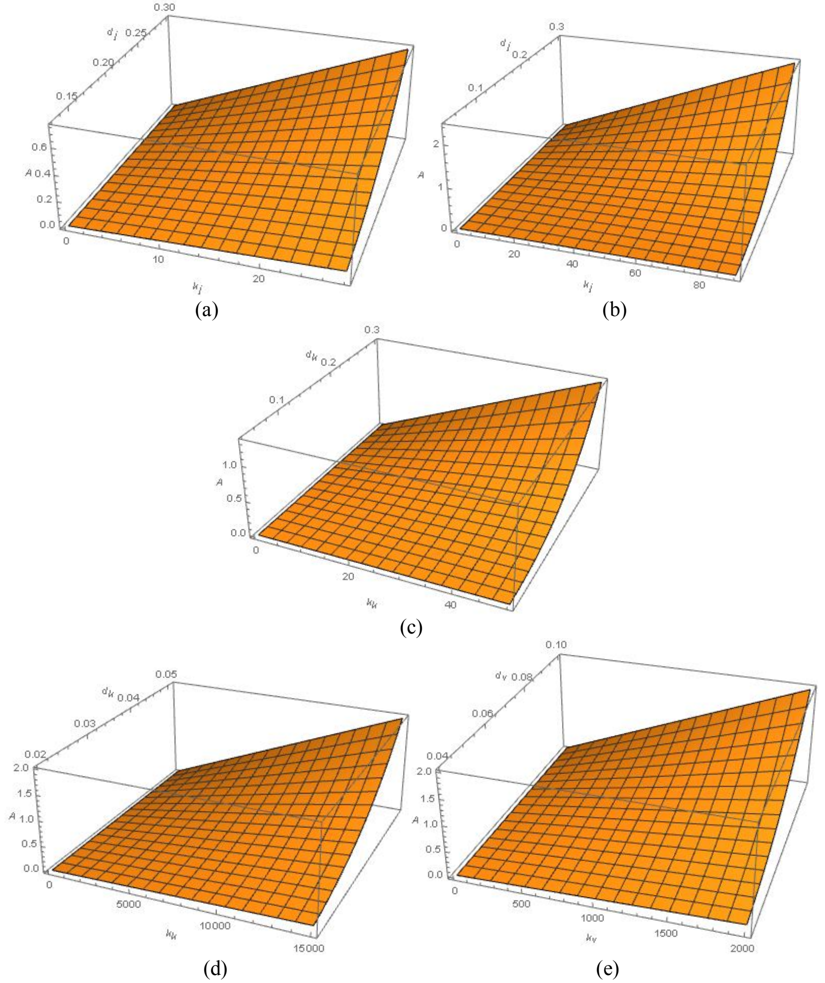

Fig. 2. Graphs of the dependence of the proportionality coefficient according to the Kirpichev-Kick theory on the energy consumed: (a) – Double Toggle Jaw Crusher; (b) – Single Toggle Jaw Crusher; (c) – Gyratory Cone Crusher; (d) – Cone Crushers Type Symons; (e) - Vibrating Jaw Crushers

The range of proportionality coefficient values is listed in Table 1. In dependence (5), the product σ2/2E reflects the proportionality coefficient. Let's enter the physical characteristics of the most common engineering materials in Table 3 and determine the value of the proportionality factor for them.

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Table 3

Physical properties of rocks

Rock type	Maximum compressive strength $\sigma_{ст}$, MPa	Young's modulus E,GPa	Coefficient of proportionality $K_{kk}=\sigma_{ст}^2/2E$
Granite	250	70	0,446
Diorite	300	100	0,45
Diabase	350	110	0,556
Basalt	300	80	0,562
Gabbro	300	100	0,45
Gneiss	200	75	0,267
Marble	250	70	0,446
Quartzite	300	90	0,5
Clay shale	100	30	0,167
Limestone	250	70	0,446
Sandstone	170	50	0,289
Dolomite	250	70	0,446
Glass	7	56	0,0004
Brick	10,3	20	0,0026
Polyethylene terephthalate (PET)	55	2,7	0,56
Acrylonitrile butadiene styrene (ABS)	40	2,3	0,347
Nylon 6	70	1,8	1,361
Polyamide	85	2,5	1,445
Polypropylene	40	1,9	0,421
Acrylic plastic (PMMA)	70	3,2	0,765
Concrete	20	23	0,008
Textolite	40	10	0,08

Taking into account formula (5) and table 2, the coefficient of energy of destruction of granite will be 0.446 J/m3 or, in terms of kg, 1.16 kJ/kg. This value corresponds to the studies presented in the sources [15], [16], [17]. However, as we can see, moving to real machines, the coefficient of destruction energy has a wide range of changes, Fig. 2. This, in turn, indicates that during the destruction of materials by a crushing machine, a large part of the energy is spent on processes that are not taken into account by the Kirpichev-Kick proportionality coefficient. Analyzing the ranges of changes in the Kirpichev-Kick coefficient, it can be seen that for shallow crushing, the range of coefficient values is significant. Based on this, it is possible to confirm the previously established regularity that the Kirpichev-Kick law better describes the processes that are within the zone of coarse crushing.

Comparing the above two hypotheses, the following can be noted. The volume hypothesis (Kirpichev-Kick law) takes into account the energy expenditure for elastic and plastic deformation of the body and does not take into account the energy expenditure for the formation of new surfaces, for overcoming the forces of external and internal friction, for energy losses associated with acoustic, electrical and thermal phenomenon, etc. The hypothesis of surfaces (Rittinger's law), on the other hand, does not take into account the expenditure of energy for elastic and plastic deformation of the body and takes into account only the expenditure of energy for the formation of new surfaces. Thus, each of the two laws discussed above operates only within a narrow framework. This led to the emergence of two additional hypotheses, the goal of which was a universal approach to determining energy consumption.

One such law is the Bond law. The essence of Bond's law is as follows: when a body is compressed, the energy is distributed over its volume, and when cracks begin to spread on the surface of the body, the energy is concentrated on the surface of the crack and is proportional to the newly formed surface [10], [13], [18], [19]. In many literary sources, Bond's law is written in a simplified form as follows:

$$A_b = K_b D^{2,5}, \tag{6}$$

where A_b – work spent on crushing, J; K_b – the Bond proportionality factor, which is determined experimentally.

However, in foreign sources, Bond's law is written in the expanded form as follows:

$$W_b = 11 W_i \left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}} \right), \tag{7}$$

where W_i – Bond performance index, kW/(short ton); P_{80} - size at which 80% of the product passes (in microns); F_{80} - is the size at which 80% of the power passes (in microns).

The Bond work index W_i represents the work required to reduce the material from an infinite size to 100 microns [18]. Dependence (7) is still a topic for numerous scientific studies, because there is no uniformly accepted methodology for determining the parameters included in this equation.

For example, in the source [18], based on numerical studies, it is noted that P80 and F80 can be determined according to the following dependencies:

$$F_{80} = 0.63G; \quad P_{80} = 0.7(L_{min} + L_t), \tag{8}$$

where G – the size of the loading hole of the crusher; L_{min} – the minimum value of the output hole of the crusher; $L_t = L_{max} - L_{min}$; L_{max} - the maximum value of the output hole of the crusher.

In another work [18], the dependencies for determining P_{80} and F_{80} have the following form:

$$F_{80} = 0.8 S_F F_{max} + 0.2 S_c; \quad P_{80} = 0.85(CSS + T), \tag{9}$$

where S_F – ore shape factor, which is determined by the ratio of the average size of an ore particle to its minimum size (varies from 1.7 for a cubic shape to 3.3 for a lamellar shape); F_{max} – the maximum size of material that is loaded into the crusher inlet; S_c – the size of the opening of the grating screen, i.e. the distance between the individual bars of the grating screen; CSS – the minimum size of the output hole of the crusher; T – the difference between the maximum and minimum outlet of the crusher.

Also, today there is a numerical variation of the methods of determining the Bond work index. Bond himself determined the performance index using a special pendulum test, which was later improved by the Metso company. The dependence for determining the work index according to Bond had the following form [18]:

$$W_i = \frac{CI}{\rho}, \tag{10}$$

where C = 53.49 – a constant that numerically and dimensionally converts the impact strength to the work index; I – impact strength, kgm/mm; ρ - density of the test sample.

Impact strength I after each test was determined as follows, kgm/mm:

$$I = \frac{2 \times m_h \times h}{d}, \tag{11}$$

where m_h – mass of the hammer, kg; h – the height to which the hammer is raised, m; d – thickness of the test sample in mm.

Among other methods for determining the Bond crushing performance index, the most famous are: the Narayanan and Whites pendulum test, the JKMRC drop test, and grinding tests in a ball and rod mill.

The fracture energy according to the Narayan and Whites test is determined as follows, kWh/t:

$$W_i = E_s\left(1-\varepsilon^2\right)\left(\frac{M_B}{M_S+M_B}\right), \tag{12}$$

where E_s – the energy of the moving pendulum (striker) to the point of impact with the test sample:

$$E_s = M_s L\left(1-\cos\alpha\right), \tag{13}$$

whereM_s – mass of the movable pendulum (hammer), kg; L – the length of the cable on which the pendulum is suspended; α- the angle of deviation from the vertical axis of the movable pendulum (striker); M_B – mass of the fixed pendulum (anvil); ε- attenuation coefficient (ε=0-0.2). In the source [18] it is noted that under the conditions of a massive stationary pendulum (anvil) the energy agrees well with the energy consumed in mills with autogenous and semi-autogenous grinding (SAG mill). On the other hand, when using a less massive anvil, the fracture energy is in good agreement with the energy consumed in rod and ball mills.

When determining the energy of destruction in the drop test (JKMRC Drop Weight test), the method developed by researcher Brown [20] is used.

Under such conditions, the energy of destruction of the sample is determined from the following dependence, kWh/t:

$$W_i = H_E \frac{0.0272M_c}{\bar{M}} , \quad (14)$$

where H_E =H–HR – the height of the fall of the load (impactor), cm; H – the height to which the load (hammer) is lifted, cm; HR – height from the base on which the test sample is placed to the load after it falls on the sample, cm; M_c – mass of the striker, kg; $\bar{M}$ - mass of the sample, kg.

For such experiments, material samples are accepted, the density of which is within 2800-4000 kg/m3. Under such conditions, the crushing energy ranges from 0.01 to 50 kWh/t for particles 10-50 mm in size.

The fracture energy determined by this method is in good agreement with the energy consumed in the fracture process in AG/SAG crushers and mills.

After the destruction of each sample by the falling mass, the fragments are collected and their size is determined, and the T10 parameter is also determined. The T10 parameter is used to determine the fracture energy and was proposed by Whedon [21]. This parameter links fracture strength and specific fracture energy. T10 is defined as the percentage of the rock that passes through the sieve and is 1/10 of the original size of the rock.

The relationship between T10 and the specific energy of destruction has the following form [22]:

$$T_{10} = A(1-e^{-bE_G}) , \quad (15)$$

where A and b constants ($A \approx 50$, $b \approx 0.4$ for hard rocks; $A \approx 80$, $b \approx 1$ for soft rocks); E_G – specific crushing energy.

The product of parameters Ab is the control parameter. When constructing a graph of the dependence of T10 on EG, the product of parameters Ab is tangent to this graph. The product Ab takes the value of 30 for hard rocks. If the value of the product Ab is in the range of 43-56, then this corresponds to medium-hard geystic rocks. If the value of the product Ab is greater than 127, then the rock is soft.

Parameter T10 can be considered an index of the degree of destruction. The harder the rock, the smaller the value of T10 for a given input energy. Knowing the value of T10 obtained as a result of the given input energy, you can calculate the complete distribution of the product by size. For crushers, the T10 value is within 10-20%.

Morrell has developed a SAG mill test (SMC test) to determine the parameters for the JK Drop Weight test. To determine the energy of destruction, the Morrell company offers the following equation [22], [23]:

$$SE = SKM_i 4\left(P_{80}^{f(P_{80})} - F_{80}^{f(F_{80})}\right), \quad (17)$$

where SE – crushing energy, kWh/t; M_i – Morel crushing performance index; K – constant (K=1 – for crushers in a closed cycle, K=1,19 – for crushers in an open cycle; S – coarse particle hardness parameter for crushing schemes that include crushers and high-pressure grinding rolls; $f(F_{80})=-(0.295+(F_{80}/1000))$; $f(P_{80})=-(0.295+(P_{80}/1000))$.

The hardness parameter of coarse particles is determined from the following dependence:

$$S=K_S\left(F_{80}P_{80}\right)^{0.2}, \tag{18}$$

where K_S – constant (for classic crushers K_S = 55, for grinding rolls of high pressure K_S = 35).

After numerous practical studies, it turned out that Bond's law is not universal and describes well the processes of destruction of the material between the zones of shallow crushing and coarse grinding [10].

In the case of considering the Bond law, we have the average value of the energy expenditure between the Kirpichev-Kick and Rittinger laws. In turn, Rebinder followed a slightly different path, namely, he defined the destruction energy as the sum of the Rittinger and Kirpichev-Kick laws [10], [24]. That is, the total work of crushing the material is equal to the sum of the work of deformation of the material of a certain volume and the work of forming new surfaces. Rebinder's law can be expressed mathematically in the following form [10], [24]:

$$A_{reb}=K_1\Delta S+K_2\Delta V, \tag{19}$$

where A_{reb}- work spent on the destruction of a solid body, J; K_1– coefficient of proportionality, J/m^2; ΔS - newly formed, upon destruction, surface, m^2; K_2 – coefficient of proportionality, J/m^2; ΔV - deformed part of body volume, m^3.

The next step in the study of energy consumption was an attempt to combine all the laws in one dependence. Such a dependence was presented by scientist A.K. Rundqvist [10], [13]. Its peculiarity is that the elementary work of crushing one piece of material is proportional to the elementary change of some degree of its size D. The dependence has the following form:

$$A_{\Sigma}=\frac{CV}{\left(K_p-1\right)D^{K_p-1}}\left(i^{K_p-1}-1\right), \tag{20}$$

where C – some constant crushing; i = D/d – degree of crushing; D and d – initial and final diameters of the crushed piece; K_p – a generalized coefficient that takes into account the amount of energy and properties of crushed material.

The graph of the dependence of crushing energy on the size of the material based on expression (8) is shown in Fig. 3.

When constructing the graph in Fig. 3, it was assumed that the volume of the material is 1 m3, the degree of crushing is i=4, and the coefficient C is equal to 1. As we can see from the graph, when choosing the appropriate value of the coefficient Kp, you can get the corresponding zones of destruction of the material. Thus, at $K_p \geq 4$, we get a zone of coarse crushing. When $2<K_p<4$, we get a shallow crushing zone, and when $K_p \leq 2$, we get a grinding zone. Also, the graph in Fig. 3 clearly shows the correspondence of the energy consumption to the size of the material that needs to be destroyed. Of course, in this case, the degree of crushing plays an important role in dependence (8). That is, the type of equipment should be taken into account, and accordingly, the process of destruction of the material.

In works [3], [21] it is proposed to determine energy according to experimental data:

$$A_{с.м.}=A_0\left[\left(100/k_{80}\right)^m-\left(100/k_m\right)^m\right], \tag{21}$$

whereA_0 – proportionality factor; k_{80} – the size of the sieve link through which 80% of the crushing product passes; m – coefficient, which is determined experimentally (m = 0,8-1,3).

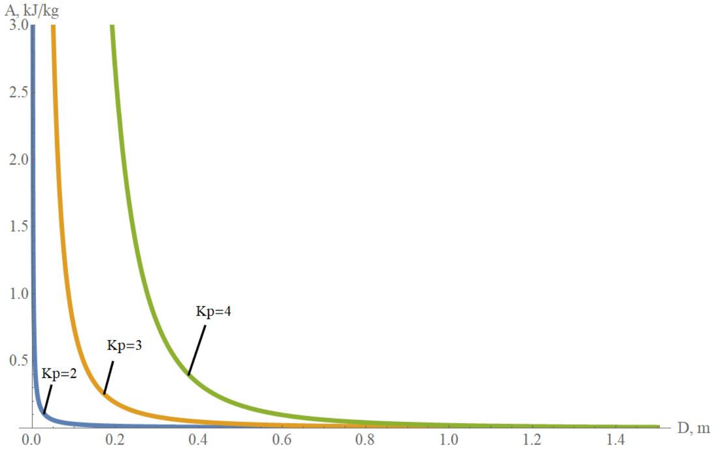


Fig. 3. Graph of the dependence of the energy of destruction on the size of the material

Coefficient$k_m$is determined by the formula[14], [21]:

$$\lg k_m = 1/5\left[\lg k_{90} + \lg k_{70} + \lg k_{50} + \lg k_{30} + \lg k_{10}\right], \qquad (22)$$

where k_{90} and k_{10} – sizes smaller than which contain 90, 70, 50, 30 and 10% of particles, respectively.

Dependence (21) was derived by J. Svensen and J. Murkes and is one of the variations of the Bond dependence (7). Basically, dependence (21) is used to determine energy consumption during grinding.

To analyze the dependence (21), we will take the following parameter values - A_0=1, k_{10} =20 mm, k_{30} =35 mm, k_{50} =50 mm, k_{70} =60 mm, k_{90} =100 mm. It should be noted that the k_m coefficient is essentially the size of the sieve link through which 80% of the raw material passes, that is, the material that just enters the crushing chamber. Calculating dependence (10) on the accepted initial values, we get that the K_m coefficient is 46.1789. Thus, the graph of the dependence of energy consumption on the size of the sieve link k_{80} has the following form (Fig. 4).

From the graph of Fig. 4, it becomes clear that if the K_{80} coefficient is equal to the Km coefficient, then the work on reducing the size of the material will not be completed. This can be seen from the graph - point 46.1789 on the abscissa axis. Therefore, the greater the difference between the K_{80} and Km coefficients, the more energy is consumed, and this can be seen from the graph in Fig. 4. The coefficient m can characterize the physical properties of materials, such as strength. So, for example, it can be seen from the graph in Fig. 4 that to reduce the size of the material from the value of Km to the size of D=20 mm with a coefficient of m=0.8, it is necessary to spend about 600 kJ. Under the same conditions, but assuming that the coefficient m will be equal to

1.3, we will receive energy consumption within the range of 42,000 kJ. Thus, the coefficient m indicates different physical properties of materials.

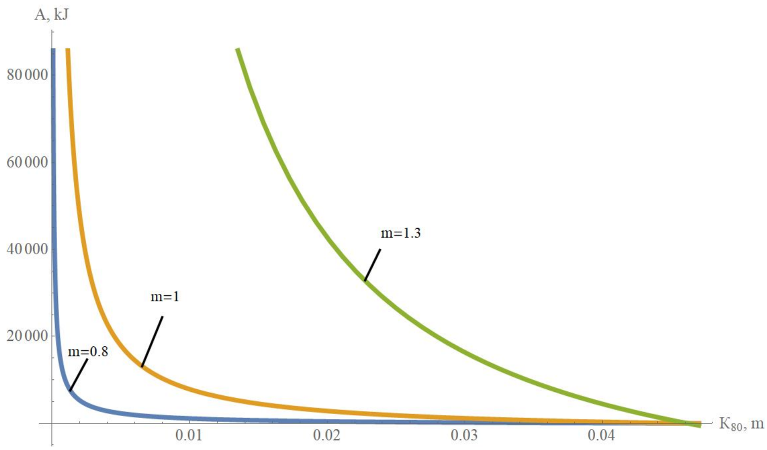


Fig. 4. Graph of the dependence of energy consumption on the size of the K_{80} sieve link

Another variant of the Bond equation is [10], [13], [19] a modified empirical equation that relates the crushing energy to the particle size of the material:

$$A_{x.} = K\left[1-(1/R)^r (100/a)^r\right], \tag{11}$$

where K – indicator of fragmentation; R – degree of crushing; a – the size of the parts of the material; r – indicator of the degree of deviation.

The value r expresses the degree of change in the resistance of the material during its crushing and the change in the efficiency of the machine with a change in particle size. Its meaning depends on the material and conditions of effort. Equation (11) can be used when crushing brittle heterogeneous materials.

In the source [19] it is noted that the act of destruction of rock with isotropic properties is staged. During the destruction of the rock in the source [10], the following four stages were distinguished: 1) the appearance of contacts and the occurrence of elastic deformations in the material; 2) the formation of a zone of comprehensive compression and its subsequent increase until the moment of the formation of an effective crack; 3) the emergence of an effective crack and its development to critical dimensions; 4) the rapid development of an effective crack until the complete destruction of the crushed material and the full consumption of the reserve of elastic energy.

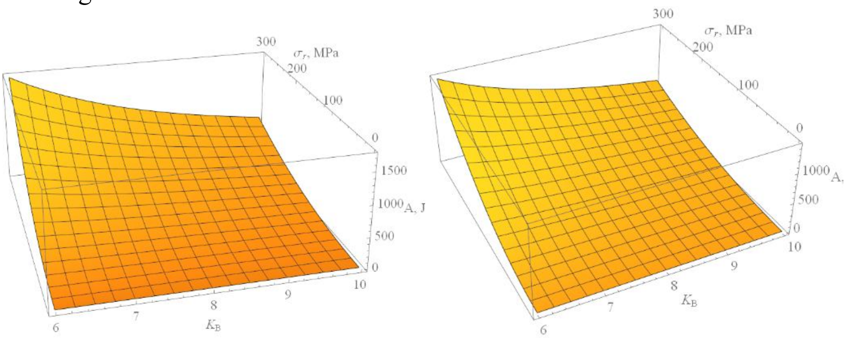
It was established that the first and second stages consume the largest amount of energy, namely 73.4%. That is, most of the destruction energy is spent on the formation of cracks in the destroyed material.

The author of these studies [10] derived a mathematical expression for determining the energy expenditure for crushing a single piece of regular shape with isotropic properties:

$$A_{RR} = \frac{3}{8}\frac{\sigma_t^2}{K_f^2 K_p^2 \sigma_{st.c} tg^2\alpha R^{0,25-0,01R}}, \tag{16}$$

where σ_t – strength limit of a piece that breaks when split; K_f – form factor in the contact zone, change limit $0.318 \div 0,5$; K_p – coefficient of proportionality; $\sigma_{st.c.}$ – ultimate (contact) stress in compression; $tg\alpha$ – coefficient of friction; R – the radius of the collapsing piece.

Let's consider the effect of the proportionality coefficient on the energy of destruction of the material from dependence (16) taking into account the values of the parameters from tables 1 and 3. For the study, we will take the value of the coefficient $K_f = 0.318$. As a test material, we will take granite with a compressive strength of $\sigma_{st.c.} = 250$ MPa. Let's take the coefficient of friction equal to $tg\alpha = 0.22$, which corresponds to the coefficient of friction of the metal against the stone.



(a) (b)

Fig. 5. The graph of the dependence of the energy of destruction on the change in the proportionality factor and the limit of strength during the splitting of the fragment that is being destroyed: (a) – R=36.5 mm; (b) – R=75 mm

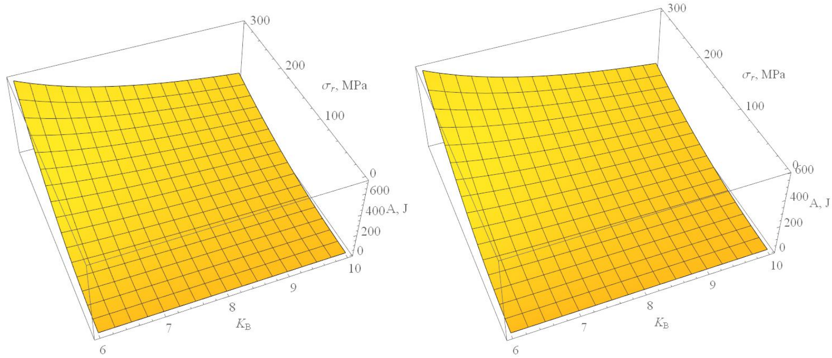
From the graphs in Fig. 5, we can see that with the increase in the size of the collapsing rock at the same values of the proportionality coefficient, the energy of collapsing decreases.

The shape factor in the contact zone has a considerable influence on energy consumption. If we take K_f=0.5, then the graphs of the dependence of the fracture energy on the change in the proportionality factor and the fracture energy will look like in Fig. 6.

From the graphs in Fig. 6, it can be seen that the influence of the size of the material on the cost of fracture energy is significantly reduced under the condition that the form factor in the contact zone is equal to 0.5.

The proposed hypothesis proves that the work spent on the single destruction of a piece of rock is proportional to the work spent on the formation of new surfaces and the friction between the formed surfaces in the zone of comprehensive compression. It should be noted here that this dependence combines two types of stress, which can cause the destruction of the material in the crushing chamber. If we compare dependence (16) with the Rittinger and Kirpichev-Kick law, the following can be noted. The Kirpichev-

Kick law considers the cost of fracture energy, which is directly proportional to the compressive stress. Rittinger's law considers the energy of destruction, which is directly proportional to the newly formed surface and thus takes into account tangential stresses.



(a) (b)

Fig. 6. The graph of the dependence of the energy of destruction on the change in the proportionality factor and the limit of strength during the splitting of the fragment that is being destroyed: (a) – R=36.5 mm; (b) – R=75 mm

Scientists D. Walker and R. Shaw proposed their own hypothesis [21], which claims that the mechanism of destruction of minerals approaches the mechanism of destruction of metals, i.e. plastic deformations appear in brittle minerals during destruction. They believed that the specific energy of grinding, by analogy with metal cutting, is constant, since the thickness of the chipped layer is less than the thickness of the layer of inhomogeneity in the material. Starting with a known critical layer thickness, the probability of encountering inhomogeneity increases, and thus the specific energy of grinding decreases. The scientists indicated that the most important variable in the destruction process is the diameter of the crushed particles, and not the area of the newly formed surface, since the effort to destroy a particle increases with a decrease in its diameter.

When conducting a number of experiments [20], [21] on the impact and quasi-static fracture of quartz, it was established that in the dynamic mode of fracture, the first impacts of the layer destroy a large number of material particles, but with subsequent impacts, the number of destroyed particles decreases. As a result, a large amount of energy is lost without the formation of a new surface. At the same time, during the slow compression of isolated quartz crystals, the area of the newly formed surface per unit of work expended is greater for an isolated crystal than for many particles. The main cause of such results is believed to be critical stresses, which at low energy concentrations are reached only at a few points, due to which long breaks occur with the formation of a small number of particles with a large surface area [10].

Under shock loads, the critical stresses grow quite quickly. Breaks spread over short distances, the newly formed surface is small, but obtained due to many particles [10], [20], [21]. When a stress pulse of sufficiently large amplitude propagates in a brittle body, it can lead to a fracture that is significantly different from the fracture under quasi-static and relatively slow dynamic loading.

The destruction caused by the stress wave is described as follows. When a compressive pulse propagating in a medium is incident normally on a stress-free boundary of that medium, it produces a tensile pulse that has the same shape as the compressive pulse, but it has a displacement directed in the opposite direction from the boundary. If the tensile stress created by the reflected pulse exceeds the tensile strength of the material, failure will occur. This phenomenon is known as "split" or "Hopkins destruction" [19], [24].

In the source [24] it is noted that when rock is destroyed by impact drilling, the energy of destruction is determined as follows:

$$E_{др} = \frac{\pi d^2 \left(tg\frac{\alpha}{2} + f \right) \sigma_{ск} v}{8}, \qquad (17)$$

where d – length of the destruction site (blade length), cm; v – speed of deepening of the working tool, mm/min; α – sharpening angle of the blade of the working tool, degrees; f – coefficient of friction of the tool material on the rock; $\sigma_{ск}$ – rock strength limit for chipping.

On the other hand, the energy during dynamic destruction can be determined from the dependence

$$E_{др}=(P_y h)/2, \qquad (18)$$

where P_y – impact force, kg; h – the depth of the working tool into the rock. In turn, the impact force is determined according to the following dependence:

$$P_y = \frac{db\sigma_0}{\cos\alpha\left(\sin\alpha - f_1\cos\alpha_0\right)}, \qquad (19)$$

where d and b – sides of the rectangular contact pad, cm; α_0–angle of inclination of the generating main pressure volume, deg; f_1 – coefficient of internal friction of the rock; σ_0 – temporary resistance of the rock to rocking. In the calculations, it is suggested to accept: $\sigma_0 \approx 0{,}185\sigma_p$– for weak rocks; $\sigma_0 \approx 0{,}204\sigma_p$ – for strong rocks.

Conclusions. So from the above we can conclude that the most widespread energy hypotheses are the Bond and Kirpichev-Kick laws. The dependencies obtained by various authors take into account, as a rule, partial problems, which are narrowly focused and do not take into account a number of factors. A large number of different approaches to solving the problem of determining energy costs for material destruction indicates the significant complexity of describing the model of material destruction by existing mathematical methods at the macro level. Thus, on the one hand, there is a need to consider the process of destruction of the material, taking into account the processes that occur at the micro level. That is, consider the process of destruction based on Rebinder's theory, namely, determine the amount of elastic energy at the micro level, and consider the amount of surface energy at the micro level. On the other hand, attempts to create a unified theory of destruction at the macro level are additionally made impossible by the stochasticity of the process itself.

Summarizing the above, the generalized theory for describing the process of destruction of materials by crushing machines should take into account the stochastic model of the description of the kinetics of the destruction process, which will take into account the features of the destruction process at the micro and macro levels.

REFERENCES

1. Kiyoo Mogi (2007) Experimental Rock Mechanics. Taylor & Francis Group, London, UK, p.362. ISBN 10: 0415394430 (print).
2. Терентьєв О.М., Стрельцова І.М. Енергоємність та питома поверхнева енергія руйнування гірських порід магнітно-гідрокавітаційнимнавантаженням. Вісник НТУУ «КПІ». Серія «Гірництво», Випуск 28, 2015р., с. 29-35 ISSN 2079-5688.
3. Vasiliev, L. M. and Vasiliev, D. L. and Malich, M. G. (2021) MODELING THE PROCESS OF DISINTEGRATION OF SOLID MATERIALS BY ASYMMETRIC LOADING IN CRUSHING MACHINES IN ORDER TO FIND WAYS TO REDUCE ENERGY COSTS. Energy- and resource-saving technologies of developing the raw-material base of mining regions. pp. 457-473.https://doi.org/10.31713/m1028.
4. Pothina, R., Kecojevic, V., Klima, M.S. et al. Gyratory crusher model and impact parameters related to energy consumption. Mining, Metallurgy & Exploration 24, 170–180 (2007). https://doi.org/10.1007/BF03403212
5. SOKUR, M.; BILETSKYI, V.; SOKUR, L.; BOZHYK, D.; SOKUR, I. Investigation of the process of crushing solid materials in the centrifugal disintegrators. Eastern-European Journal of Enterprise Technologies, *[S. l.]*, v. 3, n. 7(81), p. 34–40, 2016. DOI: https://doi.org/10.15587/1729-4061.2016.71983.
6. Jiuqun Zou, Jihuan Han, Weihao Yang, "Investigating the Influences of Indentation Hardness and Brittleness of Rock-LikeMaterial on Its Mechanical Crushing Behaviors", Mathematical Problems in Engineering, vol. 2020, Article ID 4713532, 16 pages, 2020. https://doi.org/10.1155/2020/4713532
7. Horobets L.Zh., Fedoskina E.V., Verkhorobina I.V. (2017).Jeffekty dinamichnosti nagruzhenija geterogennogo materiala pri droblenii (Effects of dynamic loading of heterogeneous material during crushing.).Geotechnical mechanics: Interdisciplinary. coll. of science works. — Dnipro: IGTM of the National Academy of Sciences,Vol. 137. p. 93-106. ISSN 1607-4556 (Print), ISSN 2309-6004 (Online). http://dspace.nbuv.gov.ua/handle/123456789/158641
8. TomislavKorman, GordanBedekovic, TrimirKujundzic, DaliborKuhinek (2014) ImpactOf Phisical And Mechanical PropertiesOf Rocks On Energy Consumption of Jaw Crusher. Physicochem. Probl. Miner. Process. 51(2), 2015, 461−475. ISSN 1643-1049 (print).
9. Khaled Ali Abuhasel (2019). A Comparative Study Of Regression Model And The Adaptive Neuro-Fuzzy Conjecture Systems For Predicting Energy Consumption For Jaw Crusher. *Applied Sciences*; 9(18):3916. https://doi.org/10.3390/app9183916.
10. Blokhin V.S., Bolshakov V.I., Malych N.G. (2006). Osnovnye parametry tehnologicheskih mashin. Mashiny dlja dezintegracii tverdyh materialov: posobie. ch.I.(Basic parameters of technological machines. Machines for the disintegration of solid materials: a manual. Part I).Dnipropetrovsk: IMA-press – p. 404 c.
11. Nazarenko I.I., Mishchuk Y.O. (2010).Analiz i ocinka energetichnih harakteristik drobarok z kerovanimi parametrami. (Analysis and assessment of the energy characteristics of shot bars with ceramic parameters). «Mining, construction, road and reclamation machines» : coll. of science works. KNUCA. Vol. 75,p. 19-24.
12. Nazarenko I.I., Mishchuk Y.O. (2012). Estimation of the energy intensity of the process of grinding building material.Construction technique. –Vol. 28,p. 20-29.
13. Nazarenko I.I. (1999).Mashini dlja virobnictva budivel'nih materialiv: Pidruchnik (Machines for the production of building materials: Textbook), K.:KNUCA, p. 488.
14. Donovan J. G., 2003, *Fracture toughness based models for the prediction of power consumption, product size, and capacity of jaw crushers*, Doctoral dissertation, Virginia Polytechnic Institute and State University.

15. Tosun A., Konak G., 2014, Development of a model estimating energy consumption values of primary and secondary crushers, Arabian Journal of Geosciences, 1-12.
16. Refahi A., Mohadesi J.A., Rezai B., 2009, Comparison between bond crushing energy and fracture energy of rocks in a jaw crusher using numerical simulation, J. South. Afr. Inst. Min. Metall., 109, 709-717.
17. Tomislav Korman, Gordan Bedeković, Trpimir Kujundžić, Dalibor Kuhinek (2015).Impact of physical and mechanical properties of rocks on energy consumption of Jaw Crusher. Physicochemical Problems of Mineral Processing. January 2015;51(2):461–475. DOI: 10.5277/ppmp150208
18. Ashok Gupta, Denis Yan (2016) Mineral Processing Design and Operations An Introduction Second Edition. Elsevier B.V. p. 856. ISBN: 978-0-444-63589-1.
19. Robert C.Dunne (2019) Mineral Processing & Extractive Metallurgy Handbook. Society for Mining, Metallurgy & Exploration, USA, p. 2258. ISBN 978-0-87335-385-4.
20. Brown D. JKMRC Internal Rep; 1992.
21. Weedon DM, Napier-Munn TJ, Evans CL. Sulphide deposits their origin and processing. London: IMM; 1990. p. 135–54.
22. Morrell S. Minerals Eng 2009;22:544–9.
23. Morrell S. Minerals Eng 2010;23:151–3.
24. Vetrov Yu.A., Baladynskyi V.L., Barannikov V.F., Kuksa V.P.(1972).Razrushenie prochnyh gruntov (Destruction of solid soils). "Builder" publishing house, Kyiv. p.352.

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АНАЛІЗ ЕНЕРГЕТИЧНИХ ЗАКОНІВ РУЙНУВАННЯ МАТЕРІАЛІВ

Число параметрів, які визначають процес руйнування матеріалів в камері дроблення є значним і важко піддається опису відомими математичними законами. Більшість теорій які описують затрати енергії на процес руйнування побудовані на емпіричних показниках та не підкріплені теоретичними основами процесу. В роботі наведено аналіз останніх досліджень в області процесів руйнування матеріалів на основі яких було встановлено, що сучасні методи визначення енергії руйнування матеріалу суттєво розрізняються між собою, базуються на різних енергетичних гіпотезах, як за прийнятими допущеннями, так і за отриманими результатами. Таким чином, відсутність загальноприйнятої моделі процесу подрібнення та єдиної методики визначення енергозатрат процесу руйнування матеріалів дробильними машинами, є тією проблемою, що потребує вирішення. З цією метою було проведено аналіз основних класичних законів руйнування матеріалів в камері дроблення. Майже всі класичні закони описуються за допомогою використання коефіцієнтів пропорційності, які враховують фізичні властивості матеріалу, затрати на тертя у вузлах машини, теплові втрати, кількість матеріалу в камері дроблення та інші параметри, що впливають на процес руйнування. Це призводить до складності визначення впливу окремих параметрів на процес руйнування, крім цього самі коефіцієнти не мають методики розрахунку і в більшості випадків визначаються експериментальним шляхом. Найбільшу кількість варіацій має закон Бонда. В якому в якості коефіцієнта пропорційності використовується параметр індексу роботи. Проте параметр індексу роботи по Бонду має широкий діапазон зміни, а також велику кількість методик його розрахунку. В цілому сама залежність гарно описує процеси між зонами мілкого дроблення та грубого помелу. В роботі для відповідних умов руйнування були встановлені межі зміни коефіцієнтів пропорційності для різних енергетичних законів. Широкі межі зміни коефіцієнтів свідчать про значну стохастичність самого процесу, та не дають вірно описати картину руйнування. Одним із варіантів інтенсифікації процесу руйнування є застосування ударного навантаження. В роботі розглянута залежність для визначення затрат енергії при динамічному руйнуванні гірських порід, що дає можливість оцінити переваги та недоліки перед статичним руйнуванням. Основними параметрами які мають вплив при динамічному руйнуванні є швидкість прикладення навантаження та геометрія поверхні робочого інструменту. На основі проведеного аналізу було встановлено, що велика кількість параметрів, які мають вплив на процес дроблення машин для виробництва будівельних

матеріалів, сильно ускладнюють на даному етапі розвитку людства створення єдиної теорії руйнування. Подальший розвиток досліджень процесів руйнування в дробильних машинах вбачається в створенні стохастичної моделі опису кінетики процесу руйнування, яка буде враховувати особливості процесу руйнування на мікро та макро рівнях.

Ключові слова: енергія руйнування, дробарка, коефіцієнт пропорційності, індекс роботи, гірські породи, ударні навантаження, степінь дроблення, розмір сита.

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ANALYSIS OF THE ENERGY LAWS OF MATERIAL DESTRUCTION

The number of parameters that determine the process of destruction of materials in the crushing chamber is significant and difficult to describe by known mathematical laws. Most of the theories that describe the energy consumption of the destruction process are based on empirical indicators and are not supported by the theoretical foundations of the process. The paper provides an analysis of the latest research in the field of material destruction processes, on the basis of which it was established that modern methods of determining the energy of material destruction differ significantly from each other, are based on different energy hypotheses, both according to accepted assumptions and according to the obtained results. Thus, the lack of a generally accepted model of the grinding process and a single method of determining the energy consumption of the process of destruction of materials by crushing machines is the problem that needs to be solved. For this purpose, an analysis of the main classical laws of destruction of materials in the crushing chamber was carried out. Almost all classical laws are described by the use of proportionality coefficients, which take into account the physical properties of the material, friction costs in the machine nodes, heat losses, the amount of material in the crushing chamber and other parameters that affect the destruction process. This leads to the difficulty of determining the influence of individual parameters on the destruction process, in addition, the coefficients themselves do not have a calculation method and in most cases are determined experimentally. Bond's law has the largest number of variations. In which the work index parameter is used as a proportionality factor. However, the parameter of the Bond work index has a wide range of changes, as well as a large number of methods for its calculation. In general, the dependence itself describes well the processes between the zones of fine crushing and coarse grinding. In the work, the limits of the change of the proportionality coefficients for various energy laws were established for the corresponding destruction conditions. The wide limits of the change of the coefficients testify to the significant stochasticity of the process itself, and do not allow a true description of the picture of destruction. One of the options for the intensification of the destruction process is the application of a shock load. The paper considers the dependence for determining the energy consumption during the dynamic destruction of rocks, which makes it possible to assess the advantages and disadvantages of static destruction. The main parameters that have an impact on dynamic destruction are the speed of load application and the geometry of the surface of the working tool. Based on the analysis, it was established that a large number of parameters that influence the crushing process of machines for the production of building materials greatly complicate the creation of a single theory of destruction at this stage of human development. The further development of research on destruction processes in crushing machines is seen in the creation of a stochastic model for describing the kinetics of the destruction process, which will take into account the peculiarities of the destruction process at the micro and macro levels.

Keywords: energy of destruction, crusher, proportionality factor, work index, rocks, shock loads, degree of crushing, sieve size.

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Міщук Є.О., Назаренко І.І. **Аналіз енергетичних законів руйнування матеріалів** // Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА, 2023. – Вип. 110. – С. .294 – 315. Англ.

В роботі наведено аналіз останніх досліджень в області процесів руйнування матеріалів на основі яких було встановлено, що сучасні методи визначення енергії руйнування матеріалу суттєво розрізняються між собою, базуються на різних енергетичних гіпотезах, як за прийнятими допущеннями, так і за отриманими результатами. Таким чином, відсутність загальноприйнятої моделі процесу подрібнення та єдиної методики визначення

енергозатрат процесу руйнування матеріалів дробильними машинами, є тією проблемою, що потребує вирішення. З цією метою було проведено аналіз основних класичних законів руйнування матеріалів в камері дроблення.
Табл. 3. Іл. 6. Бібліогр. 24 назв.

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Mishchuk Ye.O., Nazarenko I.I. **Analysis of the energy laws of material destruction** // Strength of Materials and Theory of Structures: Scientific-and-technical collected articles. – K.: KNUBA, 2023. – Issue 110. – P. 294-315.
The paper provides an analysis of the latest research in the field of material destruction processes, on the basis of which it was established that modern methods of determining the energy of material destruction differ significantly from each other, are based on different energy hypotheses, both according to accepted assumptions and according to the obtained results. Thus, the lack of a generally accepted model of the grinding process and a single method of determining the energy consumption of the process of destruction of materials by crushing machines is the problem that needs to be solved. For this purpose, an analysis of the main classical laws of destruction of materials in the crushing chamber was carried out.
Table 3. Fig. 6. Ref. 24.

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