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PROMISINGDIRECTIONSOFREDUCING SPECIFIC ENERGY COSTSIN GRINDING

Abstract. The grinding process is widely used in various technologies and is characterized by high energy consumption. Besides, there is anirretrievable loss of high-quality steel due to the wear of the working elements of grinders.

High energy costs occur not only due to the large volumes of processed materials, but also due to the extremely low efficiency of grinding machines, especially mills, the efficiency coefficientof which is at best several percents. Especially sharply the efficiency coefficientisreducing and the mills'drive capacityisincreasingwith an increase in the milling fineness of the material.

Despite the new methods of grinding: electro-hydraulic, ultrasonic, gravitational, light beam grinding, etc., in all designs of industrial units the grinding, is carried out by mechanical methods, such as crushing, cracking, impact, attrition, breakage or a combination of these methods.

There iscarried out the analysis of energy costs for formation of new surfaces, elastic and plastic deformations, for formation of various kinds of defects in the crystal structure (mainly dislocations), forfriction of the material's particles between themselves and the walls of the grinding chamber. It is noted that a small part of the input energy is consumed by different kinds of radiation (acoustic waves, exoelectronic emission, etc.), which always accompany the destruction.

From the analysis carried out it follows that the lowest energy intensity of the grinding process is achieved in grinding due to impact and slightly worse - due to crushing.When grinding by impact, the loading of the material should be pulsed with the steepest front.The loads must be dosed, corresponding to the strength and endurance of the defective zones.

To the working zone of the mill the starting material should be supplied in small volumes and even better piece by piece, and after grinding - quickly removed from the milling zone to the classifier. Therefore, any mill should operate in a closed cycle.

The classifier must be of highefficiency, so that to the finished product there came the particles of only smaller than the near-mesh grain, and the large fraction,returned to re-milling, contained as few particles of the finished product as possible.

Keywords: grinders, mills, energy costs, milling fineness, crushing, cracking, attrition, breakage, impact, classifier, closed cycle.

Introduction. Intensification of technological processes with reducing the energy costs for their implementation is an urgent task of modern production. One of the main ways to solve this problem is the creation and implementation of new high-performance machines and devices with low energy consumption.

The problem of reducing energy costs and increasing the efficiency is particularly acute in carrying out the grinding process. This process is widely used in various technologies and is characterized by high energy consumption, while the equipment for its implementation is cumbersome and has low efficiency.

Large energy consumption in the process of grinding is confirmed by the fact that about $5 \div 10\%$ of the world's electricity is spent on this process [1,p.8; 2, p. 6], and even more, according to the statistical data on the United Statesmining industry [3, 4]. Besides, the irretrievable losses of high-quality steel due to wear of the working elements of grindersare about 4 million tons per year. The mills'drive capacity in fine grinding of cement production, mining and other industries reaches up to 25MW [5, 6]. The size of mills at present has reached the limit of an economically viable size.

High energy costs occur not only due to the large volumes of processed materials, but also due to the extremely low efficiency of grinding machines, especially mills, the efficiency coefficientof which is at best several percents. Especially sharply the efficiency coefficientisreducing and the mills'drive capacityisincreasingwith an increase in the milling fineness of the material.

At the same time, by the studies of recent years, there has been revealed quite a number of mechanochemical phenomena, which are observed in fine and ultrafine grinding [7, p. 21-24]. For example, with the increase in the cementmilling fineness,thereincreases the rate of its setting and there sharply increases the strength of the agglomerate. Rocks, such as granite, schoeniteandothers, acquire cementingpropertiesin this grinding.With the increase in the milling fineness of some substances,thereincreases not only the rate, but also the degree of their dissolution. Some pigments, depending on the milling fineness, change their color. With fine grinding of ores, the process of extracting minerals is very fast, with high completeness of their extraction.In a number of works [7, p. 22] there is noted the possibility of direct metal recovery by a mechanochemical method. This is not at all a complete list of phenomena, on the basis of which it is possible to create new high-performance technologies. However, economically it is possible only on the condition of considerable reduction of costs for grinding of the materials.

The research methodology is to carry out the analysis of the main energy consumption items in grinding and to develop the recommendations onrational organization of the grinding technology with optimal process conditions.

Research results. In all designs of industrial unitsthe grinding is carried out by mechanical methods, such as crushing, cracking, impact, attrition, breakage or a combination of these methods.

In addition to mechanical methods, recently there have been proposed new methods of grinding: electrohydraulic, ultrasonic, gravitational, grinding with a light beam, obtained by means of a quantum generator, cavitational, grinding by rapidly changing high and low temperatures, grinding by a compressed gaseous mediumenergy, radiative and electromagnetic softening and others.However, the new methods have not yet come beyond the laboratory studies, and in the nearestfuture, the main units will remain mills, in which the grinding of the material is carried out by mechanical methods[2,p.8]. Hence, to reduce the energy consumption and to improve the efficiency of the grinding process, it is necessary to further improve the existing grinding units and create the fundamentally new designs.

Let's consider the main possible energy consumption items in grinding.

When grinding,theenergy is spent not only on the formation of new surfaces, but also on the elastic and plastic deformations, on the formation of various kinds of defects in the crystal structure (mainly dislocations), on the friction of material particles between themselves and the walls of the grinding chamber. A small part of the input energy is consumed by different kinds of radiation (acoustic waves, exoelectronic emission, etc.), which always accompany the destruction[2, p.153]. The value of each of the energy loss factors is not a constant value and varies quite sharply, depending on the nature of the material being destructed, the scale factor and the organization of the grinding process in each specific unit. Letusconsiderinmoredetaileachoftheaboveitems.

With the destruction of a piece of material, the new surfaces appear, with the layer of molecules of these surfaces acquiring the excess energy, the so-called "surface energy of the body." This energy must be transferred to the body from the outside. The amount of surface energy, depending on the formed surface, is determined by the following dependence [8]:

$$A = A_{yò}\Delta S \quad (1)$$

whereA – the work, spent on the increment ΔS of the surface; $A_{yò}$ – the work, spent on the formation of a unit of a new surface.

Theoretical calculations and experimental studies, conducted by many researchers,lead to paradoxical conclusions that the real strength of most minerals is two or three orders of magnitude less than the theoretical strength, while the real energy intensity of the destruction of these minerals is three or more orders of magnitude more than the theoretical energy intensity of the formation of a new surface [2, p. 34].

The differences between the theoretical strength of solids and the real one were explained by the works of A. Griffiths and A. Ioffe [9, p. 45-53; 10, p. 145-163]. According to the theory of Griffiths, strength is determined not by regular properties of the solid, but by defects, "inhabiting" it, primarily cracks.Based on this theory, he was the first to formulate an energy strength criterion, according to which a crack in a stressed body with fixed boundaries begins to develop at the moment, when it becomes energetically "profitable"tothe body, namely, when the reduction of the deformation energy of the whole body, which occurred as a result of the crack opening, exceeds the energy of the surface, formed during this opening.

Later on, the results of a series of original studies werepublishedby other scientists, having explained the nature of plastic deformation as a result of kinetic processes, occurring at the atomic level, which are associated with a discrete model of matterstructure. The defects, in this case, are in the atomic structure of the substance itself, for example, vacancies, dislocations, disclinations in crystals [11, p. 140-146; 12, p. 104- 114].

The material destruction process is to be considered as a multi-stage one and as interrelated at different scale levels. For example, it is necessary to consider the collective effects of dislocation systems, disclinations, further cracks, etc. Thus, in [13, 8] in general, the whole process of destruction is proposed to be divided into the following stages: preparatory, embryonic cracks, microcracks, macrocracks, the growth of main cracks. In certain cases, some stages may be missing.

The essential influence on energy costs in grinding is also made by the method of loading pieces of material. Thus, during compression, the elastic deformations in the milled body occur due to its loading in quasi-static or dynamic modes. In this case, the entire volume of the body is subjected to loading. At the same time, it is known that compression is far from being a rational method of destruction, and finally, the destruction occurs in those points of the body, where the tensile stresses are createdabove the critical ones.The entire volume of the piece is subjected to loading, and the work of external forces by the time of destruction becomes close to the value, when it is possible to destroy the whole sample into separate tiny particles, but the destruction occurs only on separate planes with a weakened bond.Therefore, the rest of the energy of elastic deformation, accumulated in the body, will pass into heat, that is, will be irretrievably lost. To reduce the energy consumption for elastic deformations, it would be very promising to carry out the local limit loading of the initial piece in the place of destruction.In this case, in the body the stress gradient will be observed, due to which the energy selectivity of destructionwillbeincreasing. Pilot studies of this method are being carried out in Russia under the leadership of Yu. D. Krasnikovfor the purpose of organizing the destruction of rocks with lower energy costs [14].

Some researchers [15, pp. 68–71] prove that under high speed impact loading, the compression force occurs in a certain section so fast that the crack is formed before the equilibrium distribution of energyissetinthe particle,which is necessary for making a rupture. The experimental studies on impact destruction of glass balls, given in [16, p. 1053-1060], proved that the average work of grinding by impact is approximately 42% of the grinding work by crushing.Inpaper [17] Ye. M. Gutiyar also proves that under dynamic loading of materials the stresses arising are twice higher than under static loading.Apparently, this can be explained by the fact that under high-speed dynamic loading the elastic deformation, uniform throughout the whole volume, is not yet achieved, but due to a larger stress gradient, the destruction begins in the weakened places (sections).Itshould be noted that this position is also theoretically proved in the classical course of resistance of materials [18 p. 516; 19].

When grinding materials by force loading, in addition to elastic deformations, the pieces will be subjected to plastic deformations. G. S. Khodakov [1, p. 124–126] showed in his studies that even such fragile rocks like quartzite and jaspiliteundergo plastic deformation. Thermal losses in the maximum plastic deformation can be more than a half of the entire work of destruction for most materials.

At high loading rates of the body under grinding, the plastic deformation is localized in a relatively small number of atomic layers, located directly in the region of formation of future fracture surfaces. Thus, in order to reduce the costs for plastic deformation, it is also necessary to increase the speed of loading the material with the optimally applied load.

In addition to energy losses for elastic and plastic deformations, a certain part of the energy will be spent on the formation of new defects in the crystal structure. The main part in this process will be occupied by the formation of dislocations. It should be noted that dislocations have a great influence on the strength of crystals.Under the influence of an external load, dislocations easily move, interact with each other and with other defects, unite and come to the surface of the crystal. The very displacement of the structure by at least one row of atoms weakens the crystal, in addition, the dislocations contribute to the formation of embryonic cracks, developing further into cracks of destruction [20, p. 312].

For over a hundred years many researchers have been trying to identify the patterns, permitting to quantify the energy intensity of the grinding process. The first attempt to identify the energy costs for grinding was made by P. Rittinger. According to his hypothesis, it follows that the work, spent on grinding, is proportional to the size of the newly formed surface in the materialunder grinding:

$$A_{пов} = k_{пов}\delta^2 \quad (2)$$

where $k_{пов}$ – the coefficient of proportionality.

By the supporters of this hypothesis,there were conducted numerous studies that prove the validity of the assumption of proportionality of the grinding work to the newly formed surface. However, this hypothesis does not take into account many factors, affecting the consumption energy and, above all, the energy, spent on deformation of the body without destruction.

A bit later, F. Kick and V. Kirpichev [20; 21] independently from each other put forward the hypothesis that the energy, required to obtain the similar changes in the configuration of geometrically similar bodies of the same technological structure, is changing just like the weight or volume of these bodies. Therefore, the work for grinding one piece of size δ will be equal to:

$$A_{об} = k_{об}\delta^3 \quad (3)$$

where $k_{об}$ – the coefficient of proportionality.

The experimental test has shown that the hypothesis of Kick-Kirpichevis more or less true in crushing and completely inadequate in milling.F. Bond [20], believing that the full work should include the work of deformation and formation of new surfaces, proposed to consider the work, spent on the piecegrinding,to be proportional to the geometric average of the volume and surface of the piece:

$$A = A_{об} + A_{пов} = k_{Б}\delta^{2,5} \quad (4)$$

For ball and rod mills, for hammer crushers and other designs of grinders in thegrinding of certain rocks and ores, on the basis of experimental studies,there were obtained the specific values of the proportionality coefficient $k_{Б}$ (the so-called W-index of work according to F. Bond).The industrial tests have shown good convergence of recommendations for calculation of energy costs in crushing and milling by Bond's method, which ensured its application in practical calculations.

P. A. Rebinder [20; 21] also combined the hypotheses of Rittinger and Kick-Kirpichev, considering that the destruction occurs after deformation of the piece, and the total work of crushing is equal to the sum of deformation work and new surfaces'formation work:

$$A = A_{об} + A_{пов} = k_{об}\delta^3 + k_{пов}\delta^2 \quad (5)$$

From the physical point of view, the formula of P. A.Rebinder is more correct, since it indicates the multifactorial nature of the destruction process. However, to be limited to only two factors that determine the energy intensity of the grinding process would be wrong, since in the implementation of grindingthere are a lot of other processes, proceeding simultaneously, which can consume a significant part of energy.Let's consider the main ones of them. The significant power consumption in grinding is associated with plastic deformations. Thus, in the work of G. S. Khodakov [1, p.87-89] it is shown that almost all materials are subjected to plastic deformations, no matter how fragile they are.Thus, the analysis of the surface layer of quartz particles after grinding shows that it has not a crystalline, but an amorphous structure, and the thickness of this layer depends on the time and medium, in which the grinding was performed.The calculations show that energy losses on plastic deformations are most significant at a large specific surface area of the material to be destroyed and during a long stay in the grinding zone, i.e. in fine grinding.Even such a fragile material as quartzite is subjected to plastic deformation and the energy losses for its maximum plastic deformation is about half of the entire work of destruction, and for such plastic rocks as marble and limestone – more than 80%. Since with the existing methods of grinding the plastic deformation occurs throughout the whole volume of the destroyed body, the volume of the plastic deformation region of the material's piece is proportional to the volume of this piece:

$$A_{пл} = k_{пл}\delta^3 \tag{6}$$

In addition to energy dissipation for elastic and plastic deformation, as well as energy consumption fornew surfaces' formation, a certain part of the energy will be accumulated by the body in the form of energy of various newly formed defects in the crystal structure. The decisive role in this process will be played by dislocations. The calculations, given in the literature [2, p. 34-35], show that the maximum energy density that the body can store due to dislocation distortions of the crystal structure is of the order

$$B_{к.д.\max} \approx 10^7 \; Дж/м^3 \tag{7}$$

The formation of crystal structure defects will occur in the entire volume of the material, hence the energy of defects, accumulated by the material, is proportional to δ^3, and these losses can be recorded as:

$$A_{д} = k_{д}\delta^3 \tag{8}$$

The most significant energy consumption (especially in ball mills) occurs due to external friction, which is caused by resistance, arising between the particles, contacting under the action of the compressive load, with their relative movement in the plane of contact.External friction is the result of mechanical engagement and molecular adhesion between the surfaces and further elastic and plastic displacement and scratching of the material out, with the subsequent destruction and restoration of molecular bridges between the friction surfaces.Thebulk of energy costs for external friction is not"accumulated " by the material's particles and all the more does not go to the formation of new surfaces, but dissipates into heat. Therefore, the larger the layer of material in the industrial apparatus and the higher the relative speed of the friction surfaces, the higher the energy consumption for external friction.This is confirmed by the works of German scientists of G. Rumpf's school [22, p. 79-85], which showed that the main energy losses in ball mills occur due to interaction of the material's particles.

According to calculations, made by Revnivtsev, the costs for friction of one piece are proportional to the linear size δ of the latter in the degree of 2.5. Then the costs for friction will be:

$$A_{тр} = k_{тр}\delta^{2,5} \tag{9}$$

To complete the physical picture of costs for grinding, it is necessary to take into account the costs, associated with various types of radiation. First of all, these include the acoustic waves. In the general balance of energy consumption for grinding they are small. Since radiation comes as a rule from the surface layers of the newly formed surface, these costs can be taken into account by the following expression:

$$A_{изл} = k_{изл}\delta^2 \tag{10}$$

Deeming, that we have considered all the main known energy costs for grinding, the total costs will be equal to the amount of costs for volume and plastic deformations, formation of defects, formation of a new surface, external friction and radiation:

$$A = A_{об} + A_{пов} + A_{пл} + A_{д} + A_{тр} + A_{изл} = \\ = k_{об}\delta^3 + k_{пов}\delta^2 + k_{пл}\delta^3 + k_{д}\delta^3 + k_{тр}\delta^{2,5} + k_{изл}\delta^2 \tag{11}$$

Each of the terms of this equation reflects a certain type of energy costs for processes, taking place in the grinder, and only the fourth term of the formula takes into account the useful work, spent on the formation of new surfaces. The percentage of each of the members of series (11) is not a constant value and will vary for different cases, depending on the nature of the material to be destructed, its size, the grinder's design and geometrical parameters.

The analysis of published works shows that in fine grinding of materials in the industrial designs of mills the value of useful costs, determined by the second member of the formula, does not exceed 3 percent of the total energy costs.

Of course, for further development of the grinding technology, it is necessary to develop successfully such sciences as solid state physics, fracture mechanics, etc. As for making some new "laws" of crushing, here the followingshould be noted. The natural heterogeneity of the materials, subjected to grinding, the unevenness of the stress field in the volume of the loaded piece, its anisotropy, multi-scale defects plus a variety of external factors (shape, material location, nature of movement of the machine's working parts, location of the crushed materialpieces, etc.) – make the problem of making the law of crushing, reflecting all aspects of modern technologies in terms of physics of this process, firstly, super-complex due to agreat number of parameters, and secondly, useless, because even in the hypothetical case, to use the record of a full formula of such a law would be impossible due to itsvastnesses.

In such a situation, it is quite natural that instead of the physical law for practical application there are more acceptablesimple statistical dependencies, convenient and describing close enough the phenomena in a certain range of each of the parameters of a certain design of agrinder.

However, the main task, facing both the theory and the practice of grinding, is to reduce the energy consumption in the implementation of this process. For this purpose, it is necessary to create fundamentally new, incomparably more effective methods of grinding, taking into account both the features of the natural properties of a particular material and the specifics of its further processing.First of all, it is necessary to work on the creation of more advanced designs of mills, in which the irretrievable energy losses, indicated in equation (11) by the first, third, fifth and sixth members,could be reduced to a minimum. The ways to solve this problem can be found in a detailed analysis of energy consumption items for specific structures, currently operated in the industrial production of grinding units [23-32].

Our critical analysis of the grinding process shows that the process of fine grinding (milling) is very energy-intensive, although the share of energy, spent on the disintegration of particles itself is very small and is equal to several percents. This occurs primarily due to imperfection of organization of the grinding processitself and due tolow efficiency of the equipment,applied for these purposes.

To reduce energy costs, a rational organization of the grinding process should be provided, with optimal process conditions without excessive overgrinding with minimal effort and a high degree of destruction in one working cycle.

The lowest energy intensity of the grinding process is achieved in grinding by impact and slightly worse - by crushing.

When grinding by impact, the loading of the material should be pulsed with the steepest front; the loads should be dosed, corresponding to the strength and endurance of the defective zones.

To the working zone of the mill the starting material should be supplied in small volumes and even better piece by piece, and after grinding - quickly removed from the milling zone to the classifier. Therefore, any mill should operate in a closed cycle.

The classifier must be of highefficiency, so that to the finished product there came the particles of only smaller than the near-mesh grain, and the large fraction, returned forre-milling, contained as few particles of the finished product as possible.

Conclusions.

For the process of grinding solid materials there iscarried out the analysis of energy costs for formation of new surfaces, elastic and plastic deformations,formation of various kinds of defects in the crystal structure, for friction of the material's particles between themselves and the walls of the grinding chamber, as well as for various kinds of radiation (acoustic waves, exoelectronic emission, etc.), which always accompany the destruction.

It is noted that the lowest energy intensity of the grinding process is achieved in grinding by impact and slightly worse -by crushing.

The recommendations are developed for organization of the optimal implementation of the processes of grinding and classification of solid materials.

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ҰСАҚТАУ БАРЫСЫНДАҒЫ МЕНШІКТІ ЭНЕРГИЯ ШЫҒЫНДАРЫН ТӨМЕНДЕТУДІҢ КЕЛЕШЕКТІ БАҒЫТТАРЫ

Аннотация. Ұсақтау процесі әр түрлі технологияларда кеңінен қолданыс табады және жоғары энергия тұтынумен ерекшеленеді. Одан басқа, ұсақтағыштың жұмыс элементтерінің тозуына байланысты жоғары сапалы болаттың қайтарымсыз жоғалулары болады.

Жоғары энергетикалық шығындар тек өңделетін материалдардың ауқымды көлемінен ғана емес, ұсақтаушы машиналардың аса төмен тиімділігімен түсіндіріледі, олардың пайдалы әсер коэффициенті (ПӘК) әрі кетсе бірнеше пайызды құрайды. Әсіресе материалдың ұнтақтық жұқалығы үлкеюімен диірменнің жетегінің қуаты артып бірден ПӘК-і төмендейді.

Ұсақтаудың жаңа әдістеріне қарамастан: электргидравликалық, ультрадыбысты, гравитационды, жарық сәулесімен ұсақтау және т.б., өнеркәсіптік агрегаттардың барлық конструкцияларында ұсақтау мыжғылау, ұату, соққы, ұнтақтау, сындыру сияқты механикалық тәсілдермен немесе осы тәсілдерді үйлестірумен жүзеге асырылады.

Жаңа беттердің пайда болуына кететін энергия шығындарына, серпімділік және пластикалық деформациясына, кристалды құрылымның әр түрлі ақау түрлерінің пайда болуына (негізінен дислокация), ұсақтағыш камера қабырғалары мен материал бөлшектерінің өзара үйкелісіне сараптама жүргізілді. Жеткізілетін энергияның шамалы бөлігі әрқашан қиратуларды сүйемелдейтін әр түрлі сәулеленулерге (акусттикалық толқындарға, экзоэлектронды эмиссияға) жұмсалатыны атап көрсетілді.

Жүргізілген сараптамадан ұсақтау процесінің неғұрлым төмен энергия сыйымдылығы соққы есебінен ұсақтау кезінде және біршама нашар мыжғылау есебінен қол жеткізілетінін аңғаруға болады. Соққылаумен ұсақтау кезінде материалдың жүктелуі импульсты максималды кілт аймақты болуы қажет. Жүктеме ақаулы аймақтың төзімділігі мен беріктілігіне сәйкес мөлшерлі болуы қажет.

Диірменнің жұмыс аймағына бастапқы материал шағын көлемде түсуі қажет, даналап болса тіптен жақсы және ұсақталғаннан соң ұнтақтау аймағынан жылдам шеттетіліп классификаторға жөнелтілуі қажет. Сәйкесінше, кез-келген диірмен тұйық циклда жұмыс жасауы қажет.

Дайын өнімге тек шектес бидайдан кіші бөлшектер түсу үшін, ал майдалауға қайтарылатын ірі фракция дайын өнімнің мүмкіндігінше аз бөлшегін құрауы үшін классификатор жоғары тиімділікке ие болуы қажет.

Түйін сөздер: ұсақтағыштар, диірмендер, энерго шығындар, ұнтақтыңжұқалығы, мыжғылау, ұату, майдалау, сындырылу, соққы, классификатор, тұйық цикл.

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ПЕРСПЕКТИВНЫЕ НАПРАВЛЕНИЯ СНИЖЕНИЯ УДЕЛЬНЫХ ЭНЕРГОЗАТРАТ ПРИ ИЗМЕЛЬЧЕНИИ

Аннотация. Процесс измельчения находит широкое применение в различных технологиях и отличается высоким энергопотреблением. Кроме того, происходит безвозвратная потеря высококачественной стали из-за износа рабочих элементов измельчителей.

Высокие энергетические затраты объясняются не только большими объемами перерабатываемых материалов, но и чрезвычайно низкой эффективностью измельчающих машин, особенно мельниц, коэффициент полезного действия (КПД) которых составляет в лучшем случае несколько процентов. Особенно резко снижается КПД и возрастает мощность привода мельниц с увеличением тонины помола материала.

Несмотря на новые способы измельчения: электрогидравлический, ультразвуковой, гравитационный, измельчение световым лучом и т.д., во всех конструкциях промышленных агрегатов измельчение

осуществляется механическими способами, такими как раздавливание, раскалывание, удар, истирание, разламывание или сочетанием этих способов.

Проведен анализ затрат энергии на образование новых поверхностей, на упругие и пластические деформации, на образование различного рода дефектов кристаллической структуры (в основном дислокаций), на трение частиц материала между собой и стенками измельчающей камеры. Отмечено, что незначительная часть подводимой энергии расходуется наразличного рода излучения (акустические волны, экзоэлектронную эмиссию и т.д.), которые всегда сопровождают разрушение.

Из проведенного анализа следует, что наиболее низкая энергоемкость процесса измельчения достигается при измельчении за счет удара и несколько хуже за счет раздавливания.При измельчении ударом нагружение материала должно быть импульсным с максимально крутым фронтом.Нагрузки должны быть дозированными соответствующими прочности и выносливости дефектных зон.

В рабочую зону мельницы исходный материал должен поступать в небольших объемах, а еще лучше поштучно и после измельчения быстро удаляться из зоны помола в классификатор. Следовательно, любая мельница должна работать в замкнутом цикле.

Классификатор должен обладать высокой эффективностью, чтобы в готовый продукт попадали частицы только меньше граничного зерна, а возвращаемая на домол крупная фракция содержала как можно меньше частиц готового продукта.

Ключевые слова: измельчители, мельницы, энергозатраты,тонина помола, раздавливание, раскалывание, истирание, разламывание, удар, классификатор, замкнутый цикл

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