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Evaluation the Effectiveness of the Comminution Process in a New Rotary Vibration Mill Using the Finite Element Method

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Abstract. *With the rapid development of nanotechnology the urgency of the issue of increasing the efficiency of fine and ultrafine comminution of materials has increased. Nowadays, one of the most popular issues is to obtain a grinding product with a size of less than 20 μm for various technological processes. The purpose of the investigations presented in this paper is an increasing in the effectiveness of fine and ultrafine grinding process. To achieve this purpose, the authors of the article have analyzed new technical solutions to improve the efficiency of fine and ultrafine comminution. Based on the existing principles for improving the design of stirred mills, a new design of the so-called «rotor-vibratory mill» has been proposed. Using the finite element method, the efficiency of the proposed design of the mill with the support of computer simulation of the grinding process has been evaluated. The results of the investigations showed that the new design of the mill allows to increase the product fineness by 69...75% and decrease the time of the grinding process by 60...74% in comparison with existing analogues.*

Keywords: *mill, comminution, rotor, grinding ball, vibration, impact, attrition, simulation, finite element method, stress, collision energy, number of collisions, computer simulation, particle, material destruction, Rehbinder theory.*

Introduction. Nowadays, comminution processes are applied in many areas of production (construction, mining, food, chemical, etc.). Focusing on the regional production processes implemented by enterprises of the East Kazakhstan region, the grinding process can be used in the particle size reduction of the following materials which are zinc concentrate, copper concentrate, gold-bearing flotation concentrate, granulated slag for use as a binder in concreting mines (KazZinc JSC); powders for the production of uranium pellets (Ulba Metallurgical Plant JSC); titanium concentrate, rare earth metals (tantalum, zirconium, molybdenum, niobium), bentonite clay for the production of sorbents (Ust-Kamenogorsk Titanium and Magnesium Plant JSC) [1].

The main problems existing in the comminution process are related to the increase in the energy efficiency and productivity of the process, increase in the quality of the products, and decrease in the cost of the technological process.

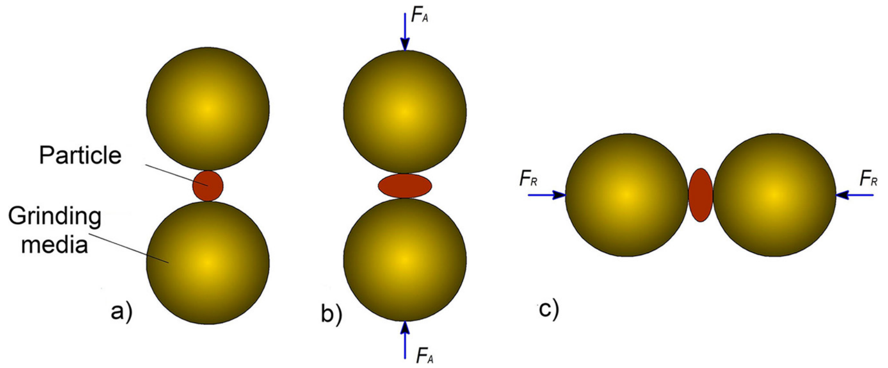
Despite a huge number of investigations on the problems of the comminution process, there are many unresolved issues obstructing the improvement of the grinding procedure. Due to the increase in the volume of processed materials the diversity of their types, the existing level of development of mills has ceased to satisfy the needs of consumers. In addition, the issue of predicting the product fineness and selecting the appropriate parameters of mills for optimizing energy costs is quite relevant. In this regard, the requirements for the designed mills have also increased. On the one hand, the designed mill should provide the required value of product fineness, and, on the other hand, it should have high energy efficiency and productivity.

Among the various types of mills, the stirred media mills widely used for fine and ultrafine grinding process [2]. To determine the principles of improving the designs of stirred media mills, various technical solutions of this type of have been analyzed based on a review of patent documents [3-5].

Based on the results of the review analysis a method for increasing the efficiency of stirred media mill has been proposed. The method is based on the position of the Rebinder theory and other known grinding models according to which the destruction efficiency increases when the material experiences high-frequency and alternating effects (Figure 1).

As follows from Figure 1, particle experiences periodic compressive and tensile stresses. As a result, a new design of the mill consisting of a vertical cylindrical chamber filled with grinding media (Figure 2) is proposed [6].

To improve the efficiency of the grinding process



a) the initial state of the particle, b) the deformation of the particle as a result of the action of axial forces, c) the deformation of the particle as a result of the action of radial forces

Figure 1 – Illustration of the mechanism describing the Rebinder effect

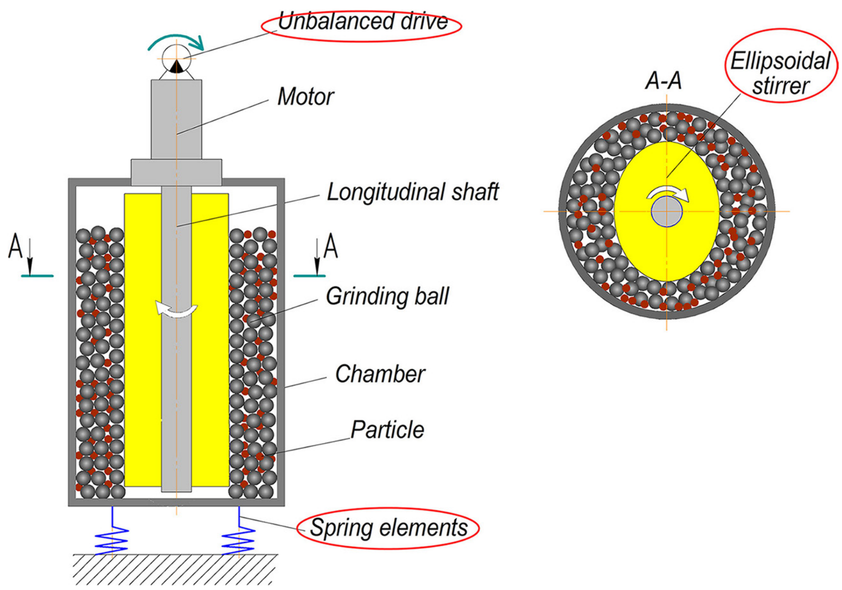


Figure 2 – A new design of the stirred media mill (rotary vibrational mill)

the following design innovations (circled in red in Figure 2) are proposed in the traditional design of the mill which are:

1) the height of the rotor is approximately equal to the height of the mill chamber;

2) the rotor is made with a new ellipsoidal profile shape;

3) the mill is supplemented with a vibration drive system consisting of an unbalanced shaft with an electric motor and elastic support elements similar to vibration vertical mills.

The aim of the investigation is to evaluate the effectiveness of grinding process (product fineness and processing time) applying the computer simulation of the grinding process considering a particle destruction by action of two grinding balls.

Simulation of the grinding process. The aim of the simulation is calculation of the stresses σ_R and σ_A emerged in the particle due to actions of forces F_R and F_A, respectively. Based on the values σ_R and σ_A, maximal product fineness and processing time of the grinding process are expected to evaluate.

To do this, the finite element method (FEM) is used in the simulation. Using the ANSYS software, the simulation has been conducted in the following consecutive actions:

1) drawing 3D-geometry of the particle (Figures 3a, 3b);

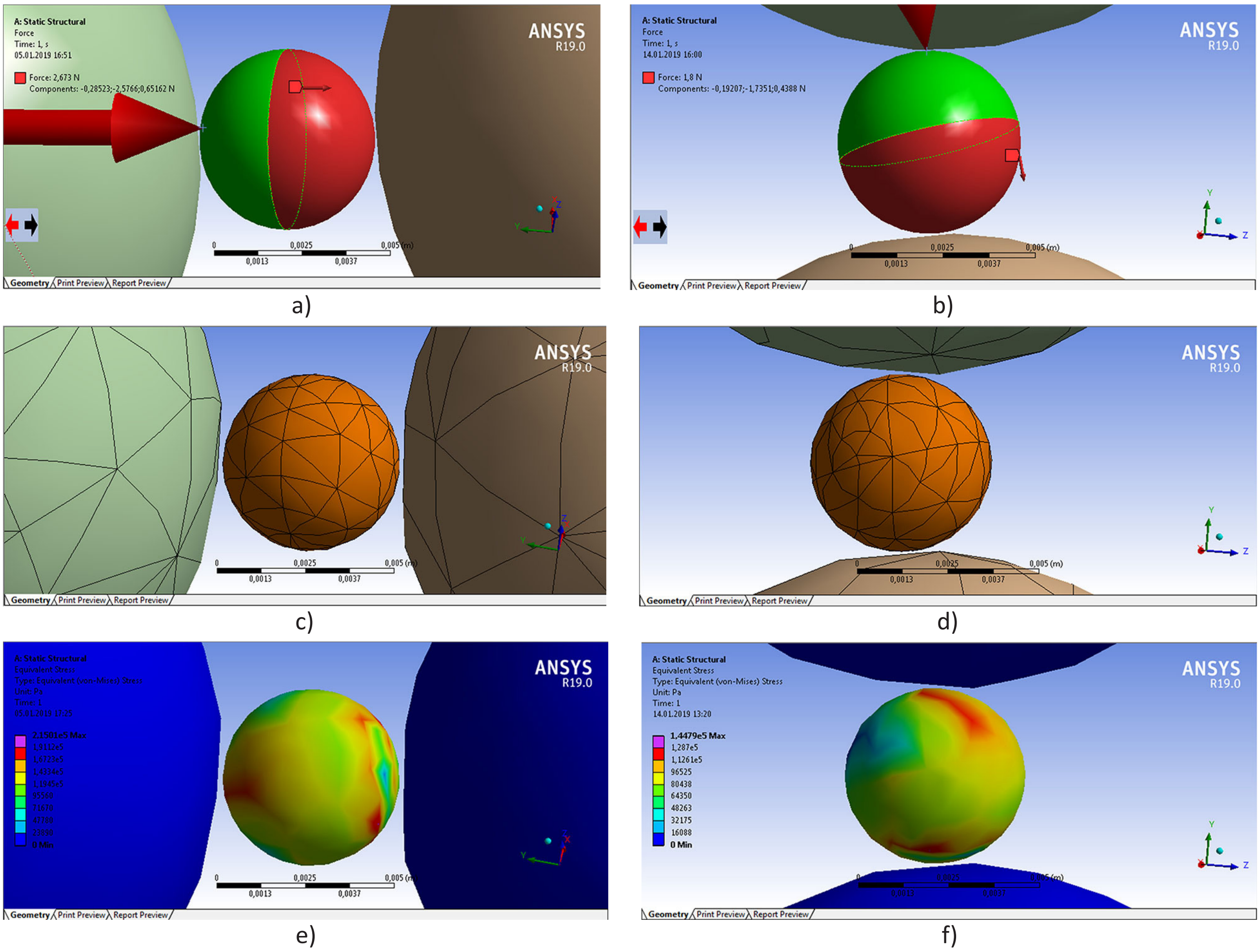
2) meshing the particle geometry (Figures 3c, 3d);

3) loading of the particle by F_R and F_A forces;

4) calculation and analysis of the particle equivalent stress distribution as a result of radial (Figure 3e) and axial (Figure 3f) loadings.

In the simulation, maximal product fineness and processing time have been evaluated as a result of only F_R action (case 1, Figure 8a), only F_A action (case 2, Figure 4b), and alternate actions of F_R and F_A (case 3, Figure 4c).

Let us describe the principle of the determining the maximal product fineness on the example of the



a), b) Geometry of the particle, c), d) Mesh of the particle, c) Radial loading of the particle, d) Axial loading of the particle, e) Particle stress distribution as a result of radial loading, f) Particle stress distribution as a result of axial loading

Figure 3 – Algorithm of the simulation

case 1 (for the cases 2 and 3 the principle is similar). As a test material, sand has been selected in the simulation. Based on the distribution of the equivalent stresses in the particle, the volume of the destructed area of the sand particle with initial size of $d_{R1} = 100$ μm has been calculated. The destructed area is the particle area in which the value of the exceeds the value of the sand particle ultimate stress $[\sigma_R]$, i.e. $\sigma_R > [\sigma_R]$. It has been modeled that remaining area (not desrtucted area) of the particle (in which $\sigma_R < [\sigma_R]$) transforms to the new spherical particle with diameter d_{R2}. Then the process is repeated. The maximal product fineness d_{Rmin} corresponds to the condition $\sigma_R < [\sigma_R]$.

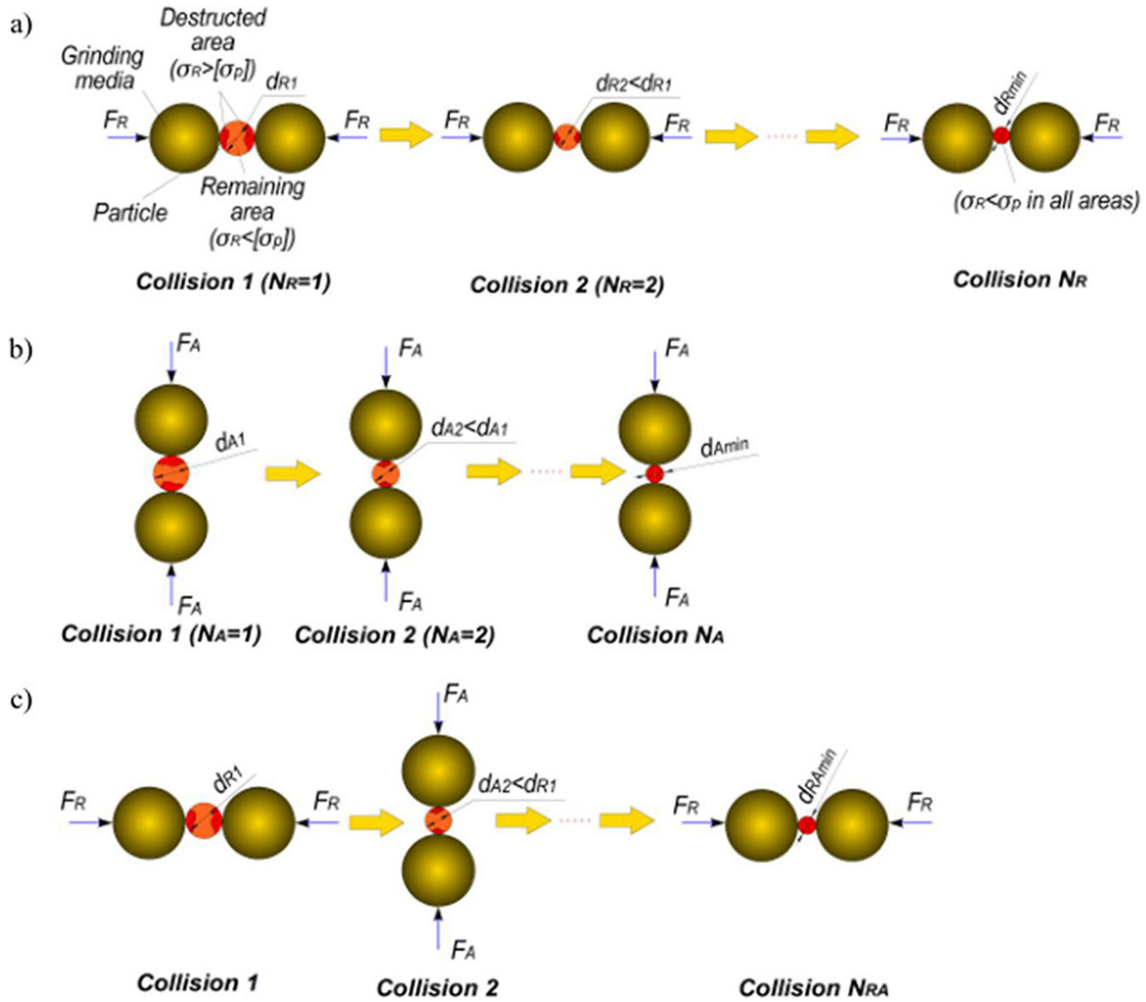
Increase in the particle ultimate stress with decrease in particle size [7] has been taken into account by the Hall-Petch equation which is $[\sigma_p] = \sigma_{p0} + k_p + (d_{p1})^{1/2}$. In the equation, σ_{p0} is the previous ultimate stress of the particle, k_p is the Hall-Petch constant ($k_p = 0.12$ MPa·m$^{1/2}$ for sand), d_{R1} is the particle size (diameter). Therefore, the value of the particle ultimate stress $[\sigma_R]$ was recalculating with decrease in particle size.

Simulation of the sand particle size reduction has been conducted using the following operational parameters: $n_R = 1350$ rpm, $n_A = 1400$ rpm, $m_{GM} = 0.0165$ kg, $b = 0.048$ m, $c = 0.028$ m, $m_A = 4$ kg, $\varepsilon = 0.06$ m, $M = 1.5$ kg, $c = 8085$ N/m^2. The values of n_R and n_A were assigned based on the operational parameters of the existing designs of the stirred media and vibration mills.

The results of the simulation for three cases of the simulation are presented in Table.

The processing time in three cases of the simulation has been determined based on the numbers of collision actions in the radial N_R and axial N_A directions (Table). Taking into account the values of n_R and n_A determining the number of the stirrer and unbalance rotation numbers per minute, the processing time in the radial t_R and axial t_A directions can be calculated as $t_R = 0.5(N_R/n_R)$ and $t_A = 0.5(N_A/n_A)$. In equations the «0.5» means that for a rotation of the ellipsoidal stirrer and the unbalance two «grinding media-particle» collisions occur.

In the third case of the simulation, the time of the grinding process t_{RA} has been calculated analogically. However, as a rotational speed n_{RA} the average value of stirrer rotational speed n_R and unbalance rotational speed n_A, i.e. $n_{RA} = (n_R + n_A)/2$ has been taken



a) Case 1; b) Case 2; c) Case 3

Figure 4 – The principal schemes of the particle destruction in the computer simulation

Results of the computer simulation

Simulation cases	Maximal product fineness	Number of collisions	Processing time	Collision force	Collision energy
1	d_{Rmin} = 32.3 μm (>20 μm)	N_R = 67500	t_{Rmax} = 25 min	F_R = 5.346N	E_R = 0.64J
2	d_{Amin} = 40.2 μm (>20 μm)	N_A = 112000	t_{Amax} = 39 min	F_A = 0.003N	E_A = 0.5312J
3	d_{RAmin} = 10.1 μm (<20 μm)	N_{RA} = 25500	t_{RAmax} = 10 min	F_R = 5.346N F_A = 0.003N	E_R = 0.64J E_A = 0.5312J

as $t_{RA} = 0.5(N_{RA}/n_{RA})$. It can be seen from Table that alternate actions of F_R and F_A forces are characterized by spending less time for the grinding process.

Conclusion. In this paper, evaluation the effectiveness of a new design of stirred media mill (which has been called as a rotary vibrational mill) has been conducted. The principle of increase in mill efficiency in increase the collision energy of the grinding media in the radial and axial directions of the mill chamber. While increase in grinding media collision energy in the radial direction has been provided by new design of stirrer in the shape of ellipse, increase in grinding media collision energy in the axial direction has been provided by the unbalanced drive with the spring elements (vertical motion of the chamber).

To evaluate effectiveness of the new design of stirred mill, the computer simulation of the sand particle size reduction has been conducted. The simulation procedure consisted in three cases which are the particle size reduction as a result of radial collision force F_R (case 1), axial collision force F_A (case 2), and alternate actions radial F_R and axial F_A collision forces (case 3). The results of the computer simulation showed that the sand particle with initial size of 100 μm can be reduced to the size of 32.3 μm (in 25 minutes), 40.2 μm (in 39 minutes), and 10.1 μm (in 10 minutes) in case 1, 2, and 3, respectively. It followes from the results of the computer simulation that the alternate actions of F_R and F_A on the particle leads to the higher grinding efficiency. It is supposed that increase in product fineness in case 3 of the simulation is a result of the Rehbinder effect implying the increase in product fineness due to emergence alternate compressive-tensile stresses in the particle.

Thus, the proposed new method of stirred media milling has provided the required product fineness (< 20 μm) spending minimal processing time. Consequently, the new design of mill can be used in large-scale industrial operations in which a high magnitude of product fineness is required.

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Ақырлы элемент әдісі арқылы жаңа роторлық-вибрациялық ұсақтағыштағы ұнтақтау үрдісі тиімділігін бағалау

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***Аңдатпа.** Нанотехнологияның қарқынды дамуы кезінде материалдарды ұнтақтау тиімділігін арттыру мәселесінің өзектілігі артты. Бүгінгі таңда ең танымал міндеттердің бірі әртүрлі технологиялық процестер үшін өлшемі 20 микроннан аз ұнтақтау өнімін алу болып табылады. Осы мақалада көрсетілген зерттеулердің мақсаты – ұсақ және өте ұсақ ұнтақтау тиімділігін арттыру. Бұл мақсатқа жету үшін мақала авторлары ұсақ және өте ұсақ ұнтақтау тиімділігін арттыру үшін жаңа техникалық шешімдерді талдады. Бисерді ұсақтағыштар конструкциясын жетілдірудің қолданыстағы принциптеріне негізделе отырып, «роторлы-вибрациялық типті» деп аталатын ұнтақтағыштың жаңа конструкциясы ұсынылған. Ақырлы элементтер әдісін қолданып, ұнтақтау процесін компьютерлік модельдеу көмегімен ұнтақтағыштың ұсынылған конструкциясының тиімділігі бағаланды. Зерттеу нәтижелері көрсеткендей, ұнтақтағыштың жаңа конструкциясы қолданыстағы аналогтармен салыстырғанда ұнтақтаудың ұсақтығын 69...75%-ға арттыруға және ұнтақтау процесінің уақытын 60...74%-ға қысқартуға мүмкіндік береді.*

***Кілт сөздер:** ұсақтағыш, ұнтақтау, ротор, ұнтақтау шары, діріл, соққы, үйкеліс, симуляция, ақырлы элементтер әдісі, кернеу, соқтығыс энергиясы, соқтығыстар саны, компьютерлік модельдеу, бөлшектер, материалды ұнтақтау, Ребиндер теориясы.*

Оценка эффективности процесса измельчения в новой роторно-вибрационной мельнице методом конечных элементов

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***Аннотация.** С бурным развитием нанотехнологий возросла актуальность вопроса повышения эффективно-*

сти тонкого и сверхтонкого измельчения материалов. На сегодняшний день одной из востребованных задач является получение продукта измельчения размером менее 20 мкм для выполнения различных технологических процессов. Цель исследований, представленных в данной статье, заключается в повышении эффективности тонкого и сверхтонкого измельчения материалов. Для достижения данной цели авторами статьи проанализированы новые технические решения по повышению эффективности тонкого и сверхтонкого измельчения. На основе существующих принципов совершенствования конструкций бисерных мельниц, предложена новая конструкция измельчителя так называемого «роторно-вибрационного типа». Используя метод конечных элементов, с помощью компьютерной симуляции процесса измельчения была оценена эффективность предложенной конструкции измельчителя. Как показали результаты исследований, новая конструкция измельчителя позволяет повысить тонкость помола на 69...75% и снизить время процесса измельчения на 60...74% в сравнении с имеющимися аналогами.

Ключевые слова: *мельница, измельчение, ротор, мелющий шар, вибрация, удар, истирание, симуляция, метод конечных элементов, напряжение, энергия столкновения, количество столкновений, компьютерное моделирование, частица, разрушение материала, теория Ребиндера.*

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