Kazak, Iryna; Sidorov, Dmytro

Article

Improvement of the structure of a ball mill with the purpose of increasing the efficiency of material crushing

Technology audit and production reserves

Reference: Kazak, Iryna/Sidorov, Dmytro (2022). Improvement of the structure of a ball mill with the purpose of increasing the efficiency of material crushing. In: Technology audit and production reserves 3 (1/65), S. 6 - 11.
http://journals.uran.ua/tarp/article/download/260278/258381/603187.
doi:10.15587/2706-5448.2022.260278.

UDC 66.03
DOI: 10.15587/2706-5448.2022.260278
Article type «Original research»

Iryna Kazak,
Dmytro Sidorov

IMPROVEMENT OF THE STRUCTURE OF A BALL MILL WITH THE PURPOSE OF INCREASING THE EFFICIENCY OF MATERIAL CRUSHING

The object of research is the design of a ball mill for grinding dry materials, the subject of research is the efficiency of grinding material based on improving the design of a ball mill.

One of the important problems for ball mills is the problem of reducing the efficiency of grinding material. The degree of grinding of materials in ball mills ensures the quality of the product. That is why this work is aimed at choosing a way to improve the design of the ball mill in order to increase the efficiency of grinding material. This will provide a better process of grinding the material in the ball mill.

The study used the analysis of the features of the ball mill designs, literature and patent review of existing ways to improve the designs of the ball mill to improve the efficiency of grinding material. As a result of the literature-patent review the method of improving the ball mill based on the prototype, which has a rotating drum with longitudinal partitions and grinding bodies, longitudinal partitions are located diametrically at right angles with windows alternating on both sides from the intersection.

It is shown that the proposed method of improving the design of the ball mill will increase the efficiency of grinding dry materials. This is due to the fact that when moving the grinding bodies and the material on the partitions there is a collision of flows, and this will increase the productivity of the ball mill. Also at the same time there will be a decrease in the moment of resistance to rotation of a drum of a ball mill that will provide economy of the electric power for its work.

In comparison with the known designs of the ball mill, the execution of diametrical partitions at right angles with prisms in the drum of the mill all the grinding bodies, and the material is moved along the partition, then half of the drum. This will increase the efficiency of grinding the material in the improved design of the ball mill.

Keywords: *mill design, grinding efficiency, fine grinding, dry materials, metal balls, diametrical partitions.*

Received date: 09.05.2022
Accepted date: 27.06.2022
Published date: 30.06.2022

How to cite
Kazak, I., Sidorov, D. (2022). Improvement of the structure of a ball mill with the purpose of increasing the efficiency of material crushing. Technology Audit and Production Reserves, 3 (1 (65)), 6–11. doi: http://doi.org/10.15587/2706-5448.2022.260278

1. Introduction

Modern productions for the production of quality cement, lime, gypsum, ceramics and other materials must provide a high degree of grinding of these materials, which further affects the quality of products from these materials. A high degree of grinding of materials is usually provided in ball mills.

The relevance of this study is that there is a need for large volumes of fine materials, which often provide ball mills of continuous action in enterprises of various industries. The possibility of production of finely ground materials of various origins with the help of ball mills in industrial volumes allowed bringing to a qualitatively new level of development the chemical and pharmaceutical industry, production of building materials, cement and more.

Therefore, the author of this paper proposes to consider one of the ways to improve the design of the ball mill in order to increase the efficiency of grinding dry materials.

The solution to the problem of improving the efficiency of grinding materials in ball mills is considered by scientists for various industries, including construction. The degree of grinding of materials in ball mills ensures the quality of the resulting product in the future of them.

2. The object of research and its technological audit

The object of research is the design of a ball mill for grinding dry materials, *the subject of research* is a way to improve the design of a ball mill to increase the efficiency of grinding dry material.

Ball mills are used in the production of cement, lime, gypsum, ceramics, etc. for grinding the material into particles smaller than tenths of a millimeter. These machines for grinding are mainly abrasive, and also have impact effects on the crushed material as a result of falling bodies grinding the material during rotation of the ball mill housing.

The method of grinding bulk materials by abrasion and impact allows obtaining a finished product of high dispersion, which is a significant advantage of obtaining crushed material in ball mills. The grinding process in ball mills is very energy intensive and expensive.

Ball drum mill is a machine for grinding material of abrasive shock action. This method of grinding bulk materials allows achieving a very high dispersion (fine grinding).

Ball mills got their name from the shape of the body and the configuration of the grinding bodies. The working volume of the mill is a cylinder with a horizontal axis of rotation. Inside the cylinder are crushed material and grinding bodies, round, spherical or cylindrical, made of various solid materials – cast iron, steel, and ceramics. Ball mills differ from crushers by finer grinding of particles – less than 0.1 mm. High-quality ball mills are able to grind raw materials to particles of 100 nm, increasing the specific surface area of the substance to 5000 cm^2/g [1].

The principle of operation of the ball mill is as follows. At a certain speed of rotation, the grinding bodies are retracted by a rotating drum, rise to the appropriate height, and then fall, performing the work of mixing the material by the percussion method. Rotation of the drum body also causes rotational movements of the layers around its axis, which grind the original product, which was between them.

Thus, when rotating the body of the ball mill, grinding metal balls, rolling and falling, erase the workpiece and have a destructive impact on it.

Ball mills have long been indispensable machines for grinding in the pharmacological and mining industries, in the production of building materials (dry mixes, cement, gypsum, bricks). These machines remain important today, because most bulk materials are ground in ball drum mills.

3. The aim and objectives of research

The aim of research is to choose a way to improve the design of the ball mill in order to increase the efficiency of grinding the material. This will allow for better grinding of the material in the ball mill.

To achieve this aim the following objectives are set:

1. To establish features of a design of a ball mill, advantages and lacks.

2. To conduct a literary-patent search for ways to improve the design of the ball mill in order to increase the efficiency of grinding material.

3. To describe and justify the method chosen to improve the efficiency of grinding the material to improve the design of the ball mill.

4. Research of existing solutions to the problem

The issues of improving the design of the ball mill are considered by the authors in the educational, patent, scientific literature in several aspects:

– technological description of the peculiarities of the grinding process in ball mills [1–3];
– achieving the effect of reducing electricity consumption by reducing the resistance of rotation of the drum [4];
– increase the productivity of the ball mill [2, 3];
– achieving increased efficiency of grinding material in a ball mill [1, 3];
– features of loading of grinding balls and its influence on efficiency of grinding of a ball mill [4, 5];
– determining the influence of quantitative characteristics (speed of rotation, the content of crushed material in the inner chamber loading of the mill) in multi-stage grinding of the material on the performance of the ball mill [6];
– selection and arrangement of parts and assemblies in a ball mill [7–9];
– simplification and acceleration of the process of control of the specific surface of the material crushed in ball mills using the apparatus of multilayer neural networks to control the grinding process with high accuracy [10].

In works [1, 2] the description of a design, the principle of action and features of a design of a ball mill is offered. It is also noted that to obtain a thinner product, ball mills operate in a closed loop with an air separator.

The source [3] considers the features of the technological process of crushing and grinding, advantages and disadvantages, modes of operation (cascade, waterfall, mixed), methods for determining productivity by the theory of similarity of ball mills. It is also noted that ball mills with central unloading are used to obtain finely ground product with a maximum size of up to 0.2 mm. The crushed product of ball mills is more uniform in size than in rod mills. To avoid re-grinding of the material, ball mills are usually used in a closed loop with hydrocyclones.

The source [4] the author offers an option to increase the efficiency of grinding the material in a ball mill by installing in the drum diametrical partitions at right angles with prisms between the windows on the partitions. Also, the ends of the partitions, if necessary, can be made bent against the direction of rotation. This design not only increases the efficiency of grinding of the mill material, but also reduces the moment of resistance to rotation.

The source [5] discusses very important issues regarding the proportion of loading of grinding bodies in the drum of the ball mill, and how it affects the efficiency of grinding the material. The performed researches are directed on development of methods of loading of a mill by grinding balls at which the thinnest grinding without loss of productivity or increase in productivity of a mill without loss of quality of grinding will be reached. To achieve the maximum fineness of grinding, it is necessary to reload balls of different diameters, which will reduce the number of voids between the grinding bodies, or stack the balls in a certain way, using in the mill lift-grooved armor plates. The proposed scheme of dense loading of grinding balls in a certain way without the use of balls of different diameters allows achieving a reduction in the volume of the void almost twice (Fig. 1).

With such a dense loading of bullets, as in Fig. 1, the entire volume is distributed as follows: 74 % – the volume of grinding balls, 26 % – the volume of voids. When using a dense load significantly increases the rate of impact compression pulse, which directly affects the quality of grinding.

The source [6], the results of experimental determination of quantitative characteristics of the efficiency of energy selectivity of grinding in drum mills are considered. In particular, it was envisaged to establish the influence of the value of the speed of rotation of the drum and the content of particles of crushed material in the load to reduce the specific energy and change the productivity of the workflow when using external chamber multistage grinding in such mills. It turned out that the use of the proposed last stage of fine grinding, compared to the traditional one-stage process, significantly reduces the specific floating energy and increases productivity at low content of crushed material in the inner chamber loading.

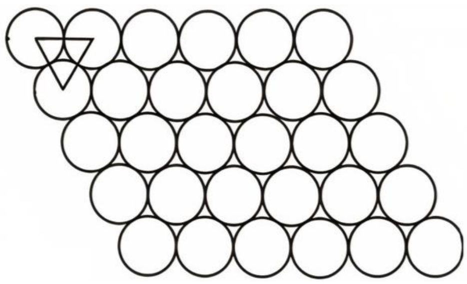


Fig. 1. Scheme of loading grinding bodies of the same diameter into a ball mill

The source [7] provides information on many problems faced by most mineral processing enterprises during the operation of the ball mill, such as low grinding efficiency, low processing productivity, high energy consumption, unstable size of the ball mill product. Thus, how to effectively increase the grinding efficiency of the ball mill is an important issue for mineral processing plants.

The source [8] presents an analysis of grinding systems used in world practice, including the main technical solutions in the field of fine grinding of materials using a ball mill, as well as indicators of their efficiency. It is established that the greatest efficiency from their use was shown by the systems of grinding of separate grinding with preliminary grinding in the press-roll grinder. However, today in different countries for deagglomeration of pressurized semi-finished products use free-standing plants that require additional space for their placement and the cost of operation and maintenance.

The source [9] proposes a method of grinding the material in a ball mill due to the fact that the grinding bodies are placed between two support surfaces. The destructive force transmitted to the material particles through the grinding body from one or both support planes does not depend on the mass of the grinding body, and is determined only by the power of the drive, due to which the support planes are moved. This allows to increase the efficiency of grinding materials in the mill and to get ready blown almost any grinding tone to nanoscale.

The source [10] the method of simplification and acceleration of the process of control of the specific surface of the material crushed in ball mills, as well as the development of a universal method of controlling the loading of the mill with the possibility of adaptation to different objects of this class. To control, it is proposed to measure the acoustic and vibration signals of the ball mill. The possibility of using as informative parameters of asymmetry and excess values of one-dimensional laws of distribution of data signals on the length of realization of more than 25000 points is investigated. The analysis of the correlation between the change in the values of asymmetry, excess and the change in the specific surface area showed the presence of a relationship between these parameters. Since the nature of the relationship between these parameters is complex, it is proposed to use the apparatus of multilayer neural networks to build the model. This method allows to approximate functions of any complexity with a given accuracy in the process of learning the network, and after learning using the information accumulated in the network as a function given implicitly. Built on the basis of this method, the measuring device allows controlling the grinding process with high accuracy, which improves the quality of the original product and reduces energy consumption.

The results of the literature and patent search show that insufficient attention is paid to the issue of more complete and efficient use of the useful volume of the ball mill drum to increase the efficiency of grinding material and reduce energy consumption of the mill. Therefore, it is necessary to find a solution that would increase the efficiency of grinding dry materials in the ball mill and at the same time help reduce electricity consumption.

The most common design of a ball mill containing a rotating drum with longitudinal partitions and grinding bodies is known. In such a mill the work of grinding bodies and material is provided either in the sliding mode, in the partition, then in the mode of impact on the drum body. The disadvantage of this design of the ball mill is the low efficiency of grinding due to the small mass of grinding bodies and material on each partition and the high moment of resistance to rotation, as at some points all the load is from below [4].

Thus, the results of the analysis allow concluding that the problem of low efficiency of grinding the ball mill is not completely solved and also that there is no universal and unique way to improve the design of the ball mill to increase the efficiency of grinding material. It is possible to note the multifaceted nature of the existing areas of research to solve this problem.

5. Methods of research

Ball mills with central unloading are most often used in various industries for grinding materials. Usually ball mills are installed in the second and third stages of grinding (rarely in the first stage). They are used for additional grinding of industrial products, as well as for grinding finely interspersed ores, when re-grinding has a negative effect on the enrichment.

The design of the ball mill with central unloading is similar to the rod mill with central unloading. Ball mill with central unloading (Fig. 2) consists of a cylindrical drum 1 with end caps 2 and 14. The drum and caps are lined inside with steel plates 8 and 10. The end caps have hollow pins 3 and 13, with which the drum rests on the main bearings 6 and 11. The rotation of the drum is transmitted from the motor through the ring gear 9 mounted on the drum. The feeder 5 of the drum or combined type is mounted on the loading pin. Hollow pins are equipped with replaceable loading and unloading funnels 4 and 12. Mills of the small sizes have hatches 7 and 15 for introduction of a lining in drums. In large mills, this operation is performed through the unloading pin. The unloading pin has a slightly larger diameter than the loading, which causes the slope of the pulp mirror in the direction of unloading in the mill [2].

Steel or cast iron balls of different diameters (from 40 to 150 mm) are loaded into the drum. The volume of the balls is about half the volume of the mill. When the drum rotates, the balls slide, roll or fall and grind the grains of the mineral. The grinding of the material occurs mainly due to the impact of the grinding bodies and partly by abrasion and crushing.

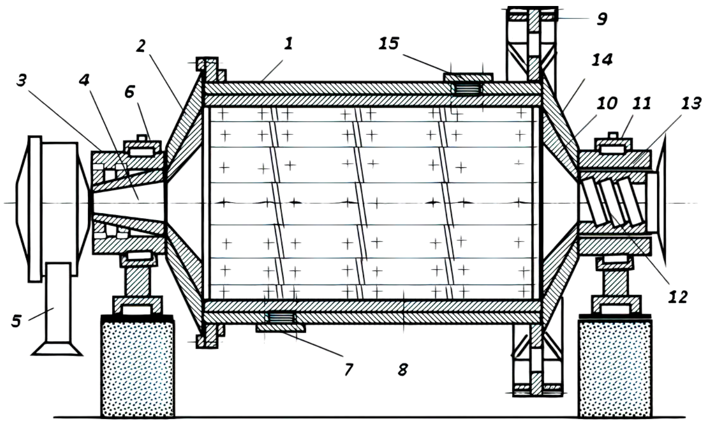


Fig. 2. Ball mill with central unloading: 1 – cylindrical drum; 2, 14 – end caps; 3, 13 – hollow pins; 4 – loading funnel; 5 – feeder; 6, 11 – bearing; 7, 15 – hatches; 8, 10 – lining plates; 9 – crown gear; 12 – unloading funnel

The source material is loaded into the mill through the loading pin, and the crushed product is unloaded from the mill through the unloading pin.

The design of a ball mill with central unloading is shown in Fig. 2 [2].

The advantages of the ball mill are: simplicity of construction, high reliability and the ability to easily adjust the degree of grinding.

Disadvantages of the ball mill: constant wear of grinding bodies, loud noise, low productivity (to achieve the result requires a long operating time – hours and sometimes days), low efficiency (slightly more than 15 %), incomplete use of space in the drum of the ball mill [3].

But, despite these shortcomings, ball drum mills are actively used in the production of various materials. According to the research topic, a literary-patent search for a way to improve the design of a ball mill was used in order to increase the efficiency of material grinding and analysis of existing methods of improving the designs of a ball mill considered in this work.

6. Research results

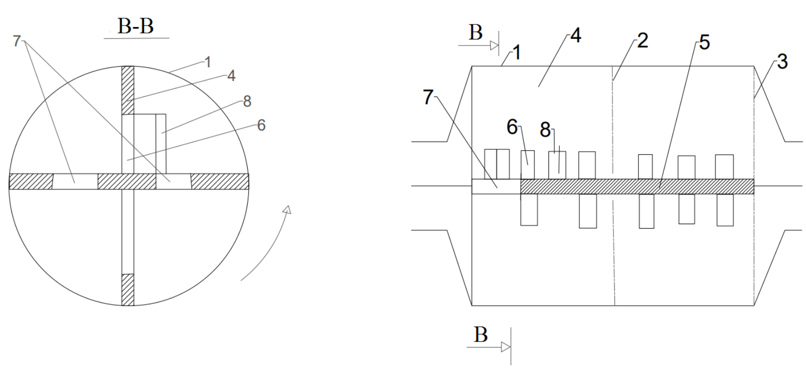
To choose a way to improve the design of the ball mill, let's take into account the features of the possible design solutions for improving the mill in order to increase efficiency and reduce the torque and the main disadvantages of ball mills. The most common disadvantage of ball mills with longitudinal partitions and grinding bodies is the low efficiency of grinding. This is due to the small mass of grinding bodies and material on each partition, and a large moment of resistance to rotation, as at certain times the entire load is from below.

As a result of the literature-patent search [1, 4, 9] of the design features and the principle of operation of the ball mill, the choice of the most expedient design of the mill was made. To eliminate such shortcomings of the ball mill as low grinding efficiency and reduce the moment of resistance to rotation of the drum, a prototype of the ball mill design was chosen, which is made with longitudinal diametrical partitions at right angles and prisms [4].

The cross section of the proposed design of the advanced ball mill with diametrical partitions and prisms at right angles is shown in Fig. 3, *a*, and the longitudinal section of the mill is shown in Fig. 3, *b*.

Consider the features of the proposed design of an advanced ball mill. The rotating drum 1 with gratings 2, 3 should intersect preferably at right angles to the diametrical partitions 4, 5, in which windows 6, 7 are made on both sides of the intersection. For example, the gaps between the windows 6 of the partition 4 are covered by a prism 8, which overlaps the window 7 in the partition 5 (Fig. 3).

The dimensions of the windows 6, 7 in radius are approximately equal to the height of the layer of grinding bodies and the material. And along the axis of the drum 1 is determined by calculation from the condition of ensuring a given interaction of flows of grinding bodies and material directed to each other by adjacent prisms 8. The dimensions of prisms 8 are determined by the size of windows 6, 7. Other dimensions are determined constructively and tested for strength and performance.



a *b*

Fig. 3. Design of an advanced ball mill with longitudinal diametrical partitions and prisms: a – cross section; b – longitudinal section; 1 – rotating drum; 2, 3 – lattice; 4, 5 – intersecting at right angles cross section diametrical partitions; 6, 7 – windows on both sides of the section; 8 – guide prism

ISSN 2664-9969

Let's consider how the advanced design of a ball mill works. When rotating the grinding body and the material first slide on the drum 1, then, the partition 5 first rises. And then begin to slide along the partition and pass through the windows 6. Moreover, if there are prisms 8, they prevent the penetration of grinding bodies and material through the windows 7, and direct the flows on both sides of the window 6 to each other. If the prism 8 is not, then part of the material and grinding bodies falls through the windows 7, and part of the inertia hits the partition 4 and still passes through the window 6.

The purpose specified in this work is achieved by the fact that the improved design of the ball mill contains a rotating drum with longitudinal partitions and grinding bodies. And the longitudinal partitions are located diametrically, at least at right angles to the windows, alternating on both sides of the center of the section of the partitions. Thus between windows on partitions directing prisms are established, and the ends of partitions if necessary can be executed bent against the direction of rotation. In the advanced design of a ball mill all grinding bodies and material move that on a partition, that on a half of a drum. These design features of the advanced ball mill will increase the efficiency of grinding the material.

The design of an improved ball mill based on the selected prototype [4] in Fig. 3 shows that the use of longitudinal diametrical partitions and prisms at right angles in the body of the ball mill will increase the efficiency of grinding. This is due to the fact that when moving the grinding bodies and the material on the partitions there is a collision of flows, and this will increase productivity. It should also be noted that the presence of partitions in one chamber at an angle of 90° reduces the moment of resistance to rotation, which will save energy.

7. SWOT analysis of research results

Strengths. The strengths of this study are that the proposed method of improving the efficiency of grinding material in a ball mill can provide on the basis of the prototype (Fig. 3) [4]:

– high quality of grinding and homogeneity of the crushed material;
– solve problems with «dead» space, as the ball mill contains walls in the drum.

The crushed mass slides between the walls of the working surface of the grinding chamber with longitudinal diametrical partitions and prisms at right angles, which provides a large number of collisions of balls with the crushed material and provides the necessary fine fraction of grinding.

Weaknesses. The weaknesses of this study are due to the fact that there is only the provision of a constructive technical solution based on the prototype of an advanced ball mill in Fig. 3, and does not quantify how much the size of the crushed material fractions will decrease. Also, this is not the only way to increase the efficiency of grinding dry material in a ball mill, but it is a very interesting way and has a right to exist.

Opportunities. Additional features of the proposed method of improving the efficiency of grinding material in a ball mill is that when moving the grinding bodies and the material on the partitions there is a collision of flows, and this will increase productivity. Also, as a result, there is a reduction in torque, which will save energy.

Threats. The method proposed in this work to increase the efficiency of grinding the material of the ball mill is theoretical. There is a need for practical elaboration and justification, which precedes a possible implementation decision.

8. Conclusions

1. It is established that the ball mill is one of the most important among the machines in the technological process for the manufacture of various types of materials, which is able to provide high grinding according to the results of sieve analysis of 90–98 %. The advantages of the ball mill are: simplicity of construction, high reliability and the ability to easily adjust the degree of grinding. Disadvantages of the ball mill: constant wear of grinding bodies, loud noise, low productivity, low efficiency (up to 15 %), incomplete use of space in the drum of the ball mill.

2. As a result of the analysis of existing ways to improve the design of the ball mill in order to increase the efficiency of grinding the material revealed a multifaceted approach of researchers to achieve this goal. These are the following ways:

– achieving the effect of reducing electricity consumption while reducing the resistance to rotation of the drum;
– achieving increased efficiency of grinding material in the ball mill due to changes in the design of the drum space or due to the peculiarities of the loading of grinding balls;
– application of the influence of quantitative characteristics (speed of rotation, the content of crushed material in the intra-chamber loading of the mill) in multi-stage grinding of the material on the performance of the ball mill;
– selection and arrangement of parts and assemblies in a ball mill;
– simplification and acceleration of the process of control of the specific surface of the material crushed in ball mills using the apparatus of multilayer neural networks to control the grinding process with high accuracy.

From the above-mentioned selected methods of improving the efficiency of grinding dry material in a ball mill, the paper focuses mainly on the method of changing the design of the mill, namely the installation of longitudinal diametrical partitions with windows at right angles and prisms. This will provide more collisions of grinding bodies and material against the partitions and will increase the efficiency of grinding the material.

3. Among the directions of increase of efficiency of grinding of material in a ball mill considered in research the most expedient and effective way of improvement of a design of a ball mill on the basis of the prototype [4] containing a rotating drum with longitudinal partitions and grinding bodies is chosen. Longitudinal partitions are located diametrically at right angles to alternating windows on both sides of the center of the partition, and between the windows on the partitions can be installed guide prisms, and can be made bent against the direction of rotation. The method chosen in the work to improve the design of the ball mill is made graphically in an automated design system in longitudinal and transverse views for clarity of representation of such a structure. Execution of the design of the advanced ball mill helps to increase the efficiency of grinding the material and reduce the moment of

resistance to rotation. The advantage of the chosen method of improving the design of the ball mill in comparison with the possible other areas of improvement considered in the study is that when performing in the rotating drum longitudinal diametrical partitions at right angles to the prisms. And also at movement of grinding bodies and material on partitions there is a collision of streams, and it will lead to productivity increase. In turn, this further helps to reduce the moment of resistance to rotation, which will save energy consumption by the ball mill.

In further research it is planned to analyze the areas of improvement of the ball mill in the wear of the lining of the rotating drum, as an important working part in interaction with grinding bodies and material for grinding. It is the lining of the ball mill that is most subject to constant wear from the impact of grinding bodies and crushed material.

References

1. Kovalenko, I. V., Malinovskii, V. V. (2006). *Navchalni doslidzhennia protcesiv, mashin ta aparativ khimichnikh virobnitctv.* Kyiv: Norita-plius, 160.
2. *Kulovyi mlyn z tsentralnym rozvantazhenniam*. Available at: https://uk.wikipedia.org/wiki/Кульовий_млин_з_центральним_розвантаженням
3. Smyrnov, V. O., Biletskyi, V. S. (2012). *Pidhotovchi protsesy zbahachennia korysnykh kopalyn.* Donetsk: Skhidnyi vydavnychyi dim, Donetske viddilennia NTSh, 284.
4. Churiumov, V. A. (1994). *Pat. No. 2014121 C1 RU. Trubnaia melnitca.* MPK: B02C 17/02. Published: 15.06.1994.
5. *Bolee plotnaia zahruzka meliushchykh tel v melnytse, kak metod dostyzhenyia bolee effektyvnoho pomola* (2018). Available at: https://energosteel.com/bolee-plotnaya-zagruzka-melyuschih-tel-v-melnitse-kak-metod-dostizheniya-bolee-effektivnogo-pomola/
6. Naumenko, Yu. V., Protsiuk, Yu. B. (2016). Enerhooshchadnist protsesu ostannoi stadii tonkoho podribnennia v barabannomu mlyni. *Naukovyi visnyk budivnytstva, 1-83,* 214–219. Available at: https://vestnik-construction.com.ua/images/pdf/1_83_2016/stroitel_1_83_2016_214_219.pdf
7. *Ten Ways to Improve the Grinding Efficiency of Your Ball Mill* (2019). Available at: https://www.linkedin.com/pulse/ten-ways-improve-grinding-efficiency-your-ball-mill-xinhai-1d
8. Romanovich, A. A., Amini, E., Romanovich, M. A. (2020). Improving the efficiency of the material grinding process. *IOP Conference Series: Materials Science and Engineering, 945 (1),* 012060. doi: http://doi.org/10.1088/1757-899x/945/1/012060
9. Bogdanov, L. K. (2015). *Pat. No. 2540537 C2 RU. Sposob i ustroistvo dlia izmelcheniia*. MPK: B02C 15/00, B02C 4/00, B02C 17/00. Published: 10.02.2015.
10. Kulaienko, O. O., Permiakov, V. I., Riabushko, A. V. (2011). *Pat. No. 95929 UA. Sposib bezperervnoho kontroliu protsesu podribnennia u kulovomu mlyni*. No. a200807258. MPK B02C 25/00. Declareted: 26.05.2008; published: 26.09.2011, Bul. No. 18.

✉***Iryna Kazak,*** *PhD, Associate Professor, Department of Chemical, Polymer and Silicate Mechanical Engineering, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Kyiv, Ukraine, e-mail: AsistentIA@meta.ua, ORCID: http://orcid.org/0000-0001-9450-8312*

Dmytro Sidorov, *PhD, Associate Professor, Department of Chemical, Polymer and Silicate Mechanical Engineering, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Kyiv, Ukraine, ORCID: http://orcid.org/0000-0002-0341-8205*

✉*Corresponding author*