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RELIABILITY PREDICTION FOR THE RUBBER LINING OPERATING UNDER EXTREME CONDITIONS

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Abstract. This work presents an analytical research of the rubber lining reliability in the ball drum mills at the first stage of quartzite grinding. The material includes a study of various factors affecting the reliability of rubber linings. Thus, it is established that design factors, that is, errors in design calculations and rubber compound formulation for the linings, amount to only 6%, that is, the design of linings is at a fairly high level. Technological factors related to the drawbacks of the technology of rubber melting and lining forming account for 12%. And the greatest share of failures - 82% - falls on operation, that is, violation of the rules of operation and non-compliance with the requirements for the operation of rubber linings exactly at the first stage of rocks grinding.

It is established that over the last forty years, reliability of the rubber lining at the 2nd and 3rd grinding stages has increased by almost 40 times - from 600-1000 hours of operation to 40,000 hours. In this work, a reliability study was carried out, which has proven the possibility of using a rubber lining of the "H-wave plate" type with increased height produced by the R&D production company "Valsa GTV" (Ukraine, Bila Tserkva), in the mills at the first stage of grinding in rather extreme conditions, namely balls with diameter of 100-125 mm and pieces of rock up to 25 mm. According to the research data in terms of the ore-dressing and processing enterprises Poltava GOK (Poltava) and SevGOK (Kryvyi Rih), the rubber lining reliability is an average of 8,000 hours.

These research data made it possible to conclude that the rubber lining resists wear quite well and absorbs the energy of the loading action, but when the wear is to the height of 115 mm top, the ability of the lining to absorb energy decreases and it gradually becomes stiffer, which contributes to the intensification of the wear process in the surface layer and to faster aging of the rubber in thickness.

A new methodology for predicting reliability of rubber linings operating under extreme conditions was developed, and comparative studies was conducted. Field tests were carried out on existing mills, and laboratory tests were carried out with using a redesigned МИ-2 friction machine. It is established that the energy of rubber destruction is $81.8 \cdot 10^{-3}$ J, density of the destruction energy is $0.18 \cdot 10^{10}$ J/m^3, time period before the lining destruction is 8305 hours.

For the МШР 3.6×4.0 mill with balls Ø 100 mm and lining of the "H-wave plate" type, the experimental reliability was determined, which was 6800 hours for the specific case and an average of 8000 hours according to the results of observation of five mills. The design reliability is 8305 hours, which indicates a fairly high accuracy of the developed methodology for predicting reliability of the lining.

Keywords: reliability, drum mill, rubber lining, wear, stiffness, energy of destruction.

Introduction. Problems of reliability and durability are the main problems for almost all industries. Improvement of modern machines is characterized by such trends as increasing the degree of their automation, loads, speeds and temperatures, reducing their dimensions and weight, increasing requirements for the accuracy and efficiency of their operation, etc.

The higher complexity of machines and increased requirements for them led to the need to increase the requirements for their reliability and durability. Each shutdown of a machine due to the damage of its individual elements or the degradation of their technical characteristics below the acceptable level prevents the effective functioning of the machine, makes it unreliable, causes material damage, and sometimes has catastrophic consequences. Today, rubber and rubber-metal linings in the drum mills operating under long-term loads are one of the basic aspects, which determines mode of operation, durability and reliability of the mill [1]. Thanks to their use, it becomes possible to essentially reduce vibrations and noise, improve durability and reliability of the machines and reduce their harmful effects on operators, and significantly improve economic performance [1, 2].

Like any applied field of knowledge, the science of reliability is based on the fundamental sciences such as mathematics and natural science, on those their branches and theoretical developments that contribute to the solution of the set tasks.

Of special importance for the science of reliability, as well as for any other science, is the application of a mathematical apparatus. During the recent years, the volume and level of the researches devoted to the probabilistic methods of structural reliability and durability calculations were increased, the fundamentals of the general theory of structural reliability based on the theory of random functions were developed, and various examples of structure reliability calculations were given [3, 4].

Usually, reliability of such elements as rubber linings is predicted by experimental (laboratory) way.

The reliability of rubber elements was investigated by such scientists as: Penkin M.S., Chyzhik E.F., Nillson G, Malyarov P.V., Powell M, Jirma S.A., Smirnov D.S., Dorokhov M.A., Racek J., Nastoyachy V.A., Nadutyy V.P. and others. All these scientists used rubber in various branches of national economies, starting from small seals in hydraulic units and ending by large-sized tires or rubber linings, the weight of which reaches tens of kilograms. Most of the works focus on improvement of qualities of the machine in which the rubber elements are used, or improvement of the design of the machine itself. The issues of reliability and durability and in particular the issue of predicting the reliability of rubber parts were relegated to the secondary plan; in most cases reliability was determined as a fact after industrial or laboratory experiments.

Predicting reliability of rubber parts is considered in more details in the works of Dyrda V.I. and Chernii O.A., Tolstenko O.V., Racek J., Powell M.S., Smit I. [4, 5, 6, 7]. In their works, the process of forming the failure of rubber parts and the criteria for evaluating their workability and durability are considered.

Having analyzed the works and the research results, it is possible to generalize that the loss of the workable condition of rubber and rubber-metal parts occurs as a result of dissipative heating and aging. However, the problem of the durability of rubber linings, considering their cost and the cost of error, needs further research.

The purpose of the work is to determine the reasons for the loss of the workable condition of rubber linings, to determine a criterion and mechanism of lining destruction, and to develop a method for predicting reliability and durability of rubber linings.

Methods. Destruction of rubber linings can be conditionally divided into three groups: design, technological and operational (Fig. 1).

The design causes for the destruction of rubber linings are related to the inconsistency of the original rubber composition with the conditions in which the lining is planned to be used, incorrect construction (geometric shape of the lining plate), and others. According to the observations and studies of the causes of failure of linings, which were carried out at SevGOK (Kryvyi Rih) and Poltava GOK (Poltava), where linings produced by the company Valsa GTV (Ukraine, Bila Tserkva) were installed at the first stage of grinding, they make up about 6% (Fig. 2).

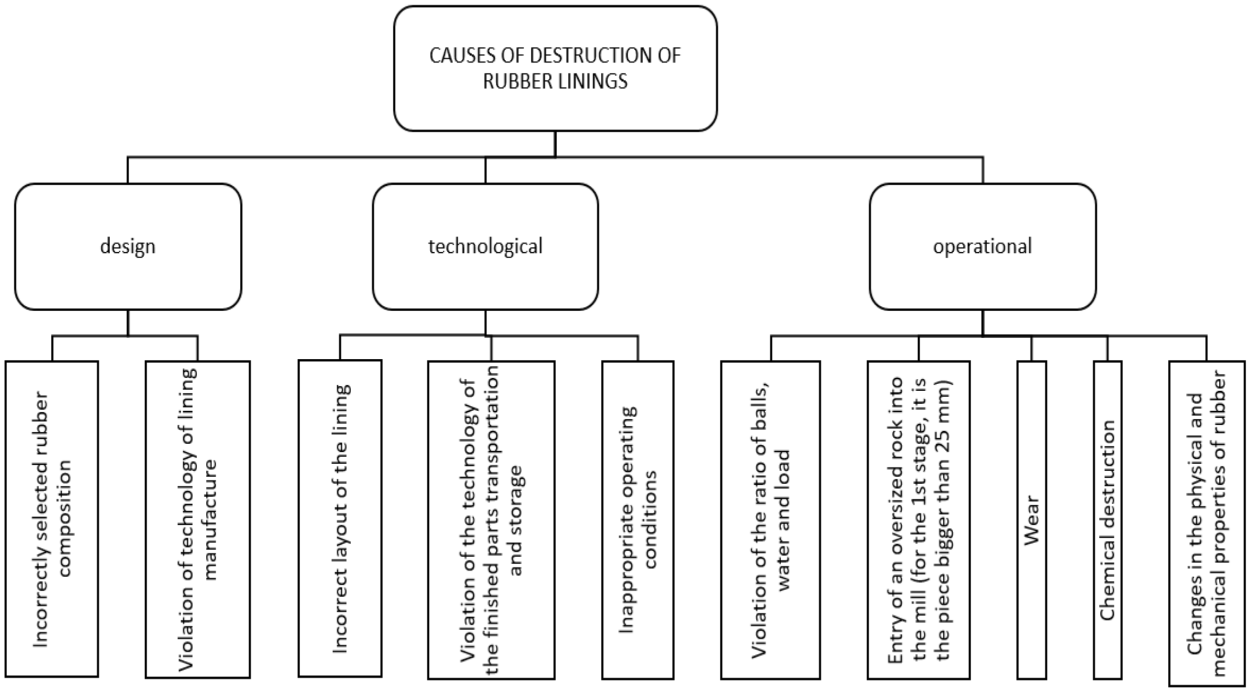


Figure 1 – Causes of destruction of rubber linings

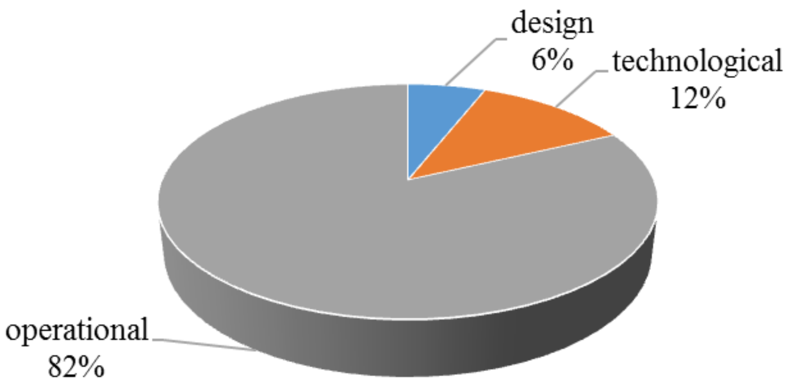


Figure 2 – Distribution of the causes of destruction of rubber linings

The technological causes are related to the violation of the technology of lining plates manufacturing and the imperfection of this process, incorrect calculation of scheme for the plates laying out and mounting in the drum of the mill. In particular, the technological factor is essentially influenced by the introduction of various modifiers into the rubber composition and their uniform distribution. Technological reasons account for about 12% of destructions (Fig. 2).

Operational destruction occurs as a result of violation of the rules of operation of the lining and the mill as a whole, violation of the rules of repair and commissioning procedures, as well as storage and transportation of the lining plates. Operational destructions make up almost 82% (Fig. 2).

Studies of the regularities of the process of destruction of rubber linings indicate significant progress in the formulation of rubbers and their manufacturing technology. Thus, the first rubber linings implemented in the 60s of the last century by the Swedish companies Skega AB and Trellex AB, which later merged into one company Metso Minerals [8], and by the Ukrainian scientists E.F. Chizhik and V.I. Dyrda back in the late 70s, had a service life of 600-1000 hours before failure. Today, thanks to the latest technologies and the introduction of nanomaterials (soot with a very fine fraction, rubber modifiers, etc.), service life of linings at the third stage of grinding is up to 40,000 hours [1, 6, 8].

Of course, it is very difficult to concretize failures, especially this applies to the technological and operational requirements where the human and other factors play a significant role. For example, the failure of the load grating went unnoticed for some period of time, and instead of 25 mm pieces, lumps of rocks 250-300 mm in size fell into the drum of the mill, which, of course, led to increased wear of the rubber lining. However, in most cases, wear of linings occurs as a result of their fatigue and aging, that is the layer of rubber being in contact with the load ages and is worn by abrasive particles present in the load (pulp). Therefore, it can be stated that the main type of wear is hydro-abrasive-fatigue wear.

Today, rubber linings work at all stages of rock crushing and sometimes under the very difficult – extreme - conditions. This is mainly the use at the first stage of grinding of balls with 100 mm and 125 mm diameter in the mills equipped with the rubber linings. When bauxite is crushed, it is a pulp with a high pH and a high temperature (in normal operating conditions, it reaches 105 °C), high rock hardness (rock hardness in Poltava GOK reaches 7 and more by the Mohs scale). Thanks to the successful design of the plates and proper formulation of the rubber, durability of the lining plates at the first stage of grinding has increased over the last decade and reaches 9000 hours [1]. Unfortunately, it is difficult to predict reliability and durability of the plates at the stage of their design and construction.

Thus, reliability of the design of lining plates can be predicted with the help of the wave theory of abrasive-fatigue wear [9] and generalized failure criteria [10]. These theories do not give a complete picture in predicting the reliability of real structures. Therefore, it is necessary to take into account operational data obtained during testing of real linings and to introduce certain correcting coefficients that can be obtained during their operation.

Since 2013, SevGOK has been testing linings in mills of the first stage of grinding with ball diameter of 100 mm. Here, the produced by the company Valsa GTV (Ukraine, Bila Tserkva) lining of the "H-wave plate" type, with increased height, that is the height of the lining is 270 mm and 240 mm, is used. The plates were arranged as follows: 270 mm plates for first 3 rows from the loading grating, and 240 mm - for the rest. The wear of plates is shown in Fig. 3 and Fig. 4.

Having analyzed the Fig. 3, it can be concluded that when lining plates are worn to a height of 115-130 mm, destructive changes begin to occur in them, that is, the action of load spread throughout the thickness of the plate and it begins to intensively change its rigidity-dissipative properties, its upper layer is intensively worn, and the next layers quickly become more stiffer and later wear out as well. Due to the increased stiffness, the rubber aggregates are broken off more easily (as less energy is spent on their breaking off) and wear occurs faster.

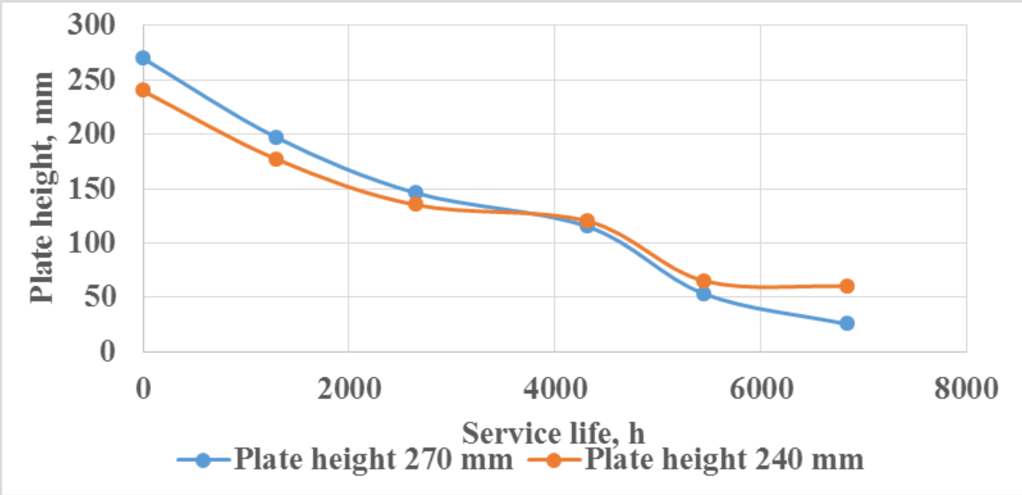


Figure 3 – Wear of lining plates

Figure 4 – Wear of linings and measurement of plate height during inspection

It is possible to predict reliability of the lining by the energy of its destruction, but the known methods for estimating the energy of material destruction have a number of disadvantages. In all cases, when investigating the energy of destruction, scratches are made by the metal pyramids; for example, in [8, 10] specific work of plastic deformation of the surface layer is calculated and equated to the activation energy of the destruction of this layer, and the activation energy is calculated by the formula:

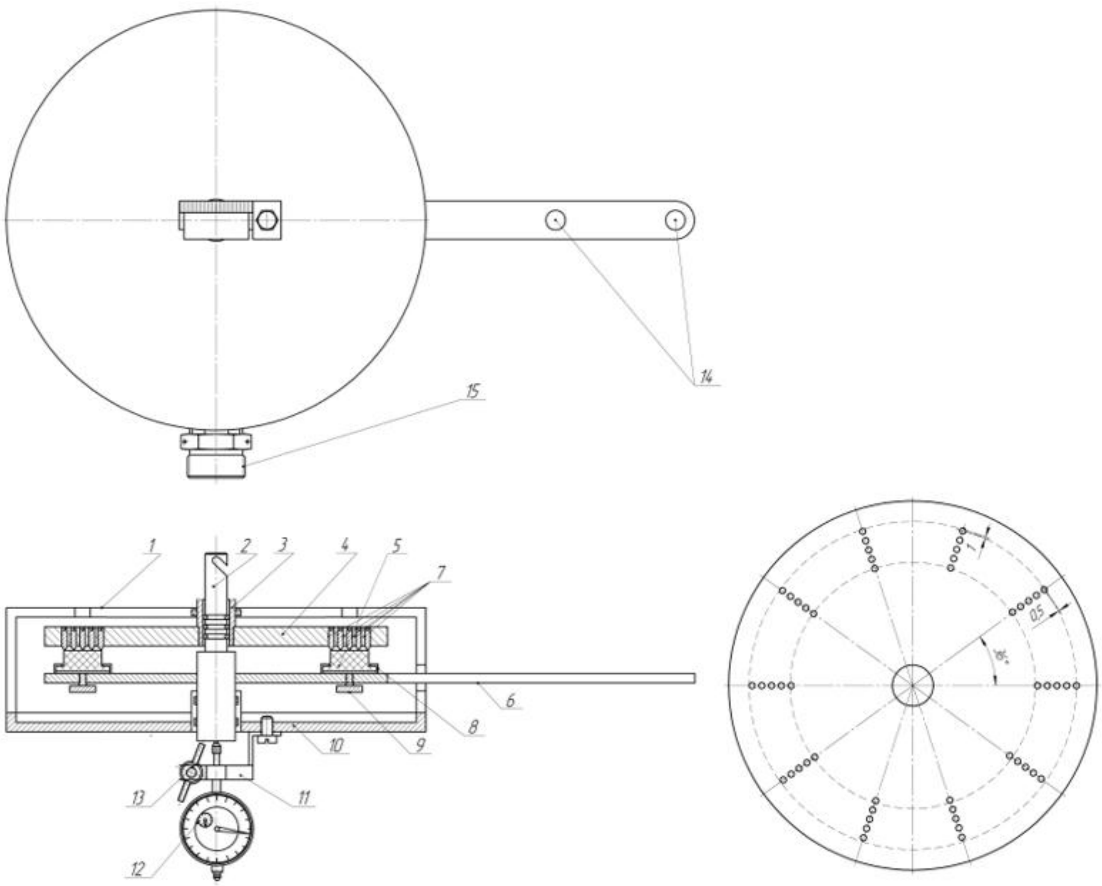
$$U_0 = \frac{0,28 \cdot F_t \cdot V_m}{h^2}, \quad \left(\frac{kJ}{mol}\right), \tag{1}$$

where F_t is the tangential resistance to plastic deformation, N; V_m is the molar volume of the material of the surface layer, mm^3/mol; h is the depth of the indenter immersion, μm.

The drawback is that it is impossible to control geometric parameters of the scratch, as it is closed up, and this method does not reproduce the process of micro-cutting and tearing off of material particles, which occurs in the case with rubber parts.

Therefore, instead of measuring the tangential force of resistance to deformation, we proposed to perform a quantitative analysis of separated rubber aggregates.

The proposed method for determining the energy of the rubber destruction is implemented as follows. A rubber sample is prepared, its worn surface is leveled and the remains of rock and ore dirt are removed. The sample is installed in the modernized МИ-2 friction machine (Fig. 5) in the plant housing 1. The pre-weighed sample of rubber in the form of a circle 5 is installed on the drive disk 4, indenters 7 are installed in the fixed indenter housings 8 and are fixed on the loading bar 6, which is connected to the loading shaft 2.



1 – plant housing, 2 – loading shaft, 3 – drive sleeve, 4 – drive disc, 5 – rubber sample, 6 – loading bar, 7 – indenters, 8 – indenter housing, 9 – adjusting screw, 10 – cover, 11 – bracket, 12 - clock-type indicator, 13 - latch, 14 - holes for attaching counterweights and dynamometer, 15 – fitting for the pneumatic system connection.

Figure 5 – The modernized МИ-2 friction machine

Depth of the scratch made by the indenter is adjusted by screwing the adjustment screw 9. Cover 10 is installed on the shaft 2 and fixed. Shaft 2 is loaded with a load, and then a clock-type indicator 12 is installed in its end with a tension of 1.5...2 turns and is fixed with a latch 13 on the bracket 11. Dynamometer and weights of a certain size are installed in the holes 14 on the loading bar.

Further, electric motor of the plant is activated, and the drive sleeve 3 with the disk 4 and the rubber sample 5 rotates, the degree of linear wear is fixed by indicator 12 and, when the required value is reached, the plant is stopped simultaneously with simultaneous activation of the pneumatic system of the plant, and the wear products are sucked out through the fitting 15. After the test, the sample is dismantled and weighed, particles of the wear products are collected and counted by using optical devices.

The energy of rubber destruction is calculated by the formula:

$$U_0 = \frac{t \cdot F \cdot V}{n} \,, \tag{2}$$

where F is the force of friction, N; t is duration of abrasion, s; V is speed of the abrasion, m/s, is the number of torn-off rubber aggregates, pcs.

Density of the energy of destruction caused by abrasive wear, that is, energy of destruction per unit of material volume, will be:

$$\Delta U_{зн} = U_0 \cdot n^* \,, \tag{3}$$

where n^* is the number of rubber aggregates in one cubic meter, pcs.

The improved accuracy of determining the energy of rubber destruction and the possibility of predicting reliability of new rubber linings and other parts operating under conditions of abrasive wear are noted, as well as the possibility of determining their residual resource during operation in comparison with the existing methods of predicting the resource, namely prediction based on linear wear [11] and thermal energy destruction [10, 12].

Results and discussion. Calculations of reliability prediction and experimental results are shown below.

Energy of rubber destruction (2), J is

$$U_0 = \frac{16 \cdot 0{,}35 \cdot 164}{11{,}227 \cdot 10^3} = 81{,}8 \cdot 10^{-3}.$$

Density of destruction energy (3), J/m^3 is

$$\Delta U_{зн} = U_0 \cdot n^* = 81{,}8 \cdot 10^{-3} \cdot 22 \cdot 10^9 = 0{,}18 \cdot 10^{10}.$$

Total energy of destruction of rubber lining, J/m^3 is

$$\Delta U_p^* = \Delta U_y^* + \Delta U_{зн}^* = (1{,}34 + 0{,}18) \cdot 10^{10} = 1{,}52 \cdot 10^{10}. \tag{4}$$

The number of cycles before the destruction of the rubber lining, cycles, is

$$N^* = \frac{\delta_м \cdot \eta_ф \cdot \Delta U_p^*}{0,5 \cdot E_д \cdot \varepsilon^2 \cdot \psi \cdot (1-\eta_T) \cdot f(x,y,z)} = \\ = \frac{1,10 \cdot 1,15 \cdot 1,23 \cdot 10^{10}}{0,5 \cdot 5,8 \cdot 10^6 \cdot 0,046^2 \cdot 0,66 \cdot 0,28 \cdot 1,4} = 0,099 \cdot 10^8, \quad (5)$$

where: $\delta_м$ is the coefficient, which characterizes the effect of the asymmetrical loading of the mill along its length; $\eta_ф$ is the coefficient, which characterizes the rubber lining profile; $E_д$ is the Young's dynamic modulus, Pa; ε is relative compression, mm; ψ is energy dissipation coefficient; η_T is correction coefficient; $f(x,y,z)$ is the function of distribution of stress and strain fields.

Time period before destruction of the lining, h, is

$$t^* = \frac{N^*}{\omega} = \frac{0,099 \cdot 10^8}{0,33} = 0,299 \cdot 10^8 c = 8305, \quad (6)$$

where: ω is drum rotation speed, rpm.

Therefore, the predicted reliability of the rubber lining is 8305 hours, which almost coincides with the reliability of the lining which worked in the drum mill МШР 3.6×4.0 with balls Ø 100 mm having the service life of 6800 hours, according to Fig. 3. Today, the average service life of rubber lining in drum mills of the first grinding stage is 8,000 hours [1], which almost coincides with the predicted reliability.

Conclusion. It was established that typical wear of rubber linings is the hydroabrasive-fatigue wear. For the МШР 3.6×4.0 mill with balls Ø 100 mm and lining of “H-wave plate” type, the experimental reliability is established, which is 6800 hours for the specific case and an average of 8000 hours according to the results of observation of five mills. The design reliability is 8305 hours, which indicates a fairly high accuracy of the developed methodology for predicting the reliability of the lining.

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ПРОГНОЗУВАННЯ НАДІЙНОСТІ ГУМОВОЇ ФУТЕРОВКИ, ЯКА ПРАЦЮЄ В ЕКСТРЕМАЛЬНИХ УМОВАХ

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Анотація. У даній роботі представлено аналітичне дослідження надійності гумових футеровок кульових барабанних млинів першої стадії подрібнення кварцитів. Матеріал включає дослідження різних факторів на надійність гумової футеровки так визначено, що конструктивні фактори, тобто прорахунки при проектуванні та підборі рецептури гумових сумішей футеровок складають лише 6 %, тобто проектування футеровок знаходиться на досить високому рівні. Технологічні фактори пов'язані з недоліками технології варки гуми та формування футеровок складають 12 % і найбільша доля відмов припадає на експлуатацію, тобто порушення правил експлуатації та недотримання вимог щодо експлуатації гумових футеровок саме на першій стадії подрібнення порід і складає 82 %.

Встановлено, що за останні сорок років надійність гумової футеровки виросла для 2-ї та 3-ї стадій подрібнення майже в 40 разів з 600-1000 годин роботи до 40000 годин. В роботі проведено дослідження надійності та доведено можливість застосування гумової футеровки типу «плита-Н-хвиля» збільшеної висоти виробництва НПП «Валса ГТВ», Україна, м. Біла Церква на млинах першої стадії подрібнення в досить екстремальних умовах, а саме кулі діаметром 100 -125 мм, шматки породи до 25 мм. Надійність гумової футеровки становить в середньому 8000 годин по даним досліджень на ПолГЗК м. Полтава та на ПівнГЗК м. Кривий Ріг.

Данні досліджень дали змогу зробити висновок, що гумова футерівка досить добре опирається зносу і поглинає енергію дії завантаження але при зносі до висоти 115 мм здатність поглинати енергію футеровкою зменшується і вона поступово жорсткішає, що сприяє інтенсифікації процесу зносу поверхневого шару і більш швидкому старінню гуми по товщині.

Розроблено та проведено порівняльні дослідження методики прогнозування надійності гумової футеровки, що працює в екстремальних умовах. Натурні випробування проводились на реальних млинах, а лабораторні за допомогою модернізованої машини тертя МИ-2. Встановлено, енергія руйнування гуми складає 81,8·10^{-3} Дж, щільність енергії руйнування 0,18·10^{10} Дж/$м^3$, час до руйнування футеровки 8305 годин.

Для млина МШР 3,6×4,0 з кулями Ø 100 мм і футеровкою типу «плита-Н-хвиля», встановлено експериментальну надійність, яка становить 6800 годин для конкретного випадку та в середньому 8000 годин за результатами спостереження за п'ятьма млинами. Розрахункова надійність становить 8305 годин, що свідчить про досить високу точність розробленої методики прогнозування надійності футеровки.

Ключові слова: надійність, барабанний млин, гумова футеровка, знос, жорсткість, енергія руйнування.

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