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THE SCOOP FEEDER AS A MEANS OF RESOURCE SAVING IN BALL MILL GRINDING OF FEED ORE WITH CLASSIFIER SANDS

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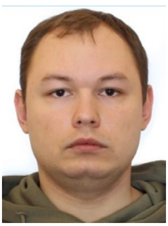

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Abstract. The subject of the research is a new approach of resource-saving adaptive distributed control of ore grinding with sands of mechanical single-spiral classifier in ball mills on the basis of taking into account the role of scoop feeder, influence on material flows, estimation of technological parameters with increased accuracy and new mathematical models of water dosing in the technological process and algorithm of estimation of solid concentration in the pulp of technological unit. Within the framework of the adopted research methodology a number of methods of different accessory groups have been applied. Comparison method – when studying the statics of the scoop feeder and its operation with one and two gripping bodies. Method of analysis – at increase of resource saving in the process of grinding of raw materials, means and approaches of stabilisation of pulp liquefaction in ball mills, prediction of errors of solid/liquid ratio, inclusion of the initial section of the mill in active work. Method of mathematical modelling – in the development of a mathematical model for finding the mass flow rate of solid in the sand flow, finding the water flow rate into the ball mill at various technological points. Method of the theory of algorithmic estimation – in the development of an approach for identification of the solid/liquid ratio in the ball mill. Method of error theory – in measuring pulp volumetric flow rate. Flowmeter theory methods – in measuring the volumetric flow rate of water and slurry. Methods of the theory of scanning devices – at creation of volumetric flow meter of pulp in open flow. The aim of the publication is to investigate the scoop feeder as a means of resource saving in a ball mill when grinding ore with classifier sands based on the application of new models of the technological process, a new algorithm for assessing the concentration of solid in the pulp, control of the oscillation of material flows and models of water flow rate stabilisation. The purpose of the research has been achieved. The obtained results are a theoretical basis for the creation of a system of adaptive separate resource-saving control of ore grinding with classifier sands in the first stages of ore preparation.

1. Introduction

Ukraine is among the top ten countries producing ferrous metallurgy products. The products of domestic metallurgical and mining and processing plants account for the overwhelming share of export revenues. At the same time, the industry's products are characterised by high production costs, compared to those of foreign partners, and are of somewhat lower quality and significantly higher specific costs of electrical energy and materials. Therefore, there is an urgent need to solve the problem of overcoming the insufficient level of competitiveness of these types of domestic products in the world market. Since now the share of magnetite concentrates in iron ore raw materials is more than half, providing a lower cost of metal compared to smelting it from rich ores, and rich ores at this stage also need beneficiation, the relevant technological processes need to be transformed in the direction of improving their economic performance.

2. Actuality of the paper

Depending on the quality of the initial ore and the final product size, power consumption for grinding accounts for 55-70% of the total expenditure of this type of energy at the concentrator. The determining technological parameter is pulp liquefaction in ball mills, because only at a certain value of this parameter optimal conditions for the operation of balls and material movement along the mill drum are created. The pulp liquefaction in a ball mill depends on the type of ore and its size. As it is known, the necessary optimal pulp liquefaction in ball mills can be achieved and maintained only automatically. However, no effective systems of automatic control of this process have been created so far, and the capabilities of the scoop feeder as a controlled object have not been utilised, despite the considerable amount of research carried out in this direction. Successful solution of the automation issue would open prospects for realisation of a number of potential opportunities - increase in productivity of ball mills, significant reduction of power, ball and lining consumption, improvement of quality of the finished product, reduction of iron losses. This is especially important in the first stages of grinding, where the expenditure of energy and materials in the form of balls and linings is the most significant.

3. Unresolved parts of a common problem

Among the unresolved parts of the problem we can single out the processes of control of technological redesigns of ball grinding of iron ore at ore dressing plants in closed cycles, including ball mill, mechanical single-spiral classifier and scoop feeder, as well as a set of automated systems for energy-efficient control of ore grinding-classification as part of the automated control system of the technological process of the first stage of ore preparation on the basis of the developed methodology. The role of the scoop feeder in resource saving in ore preparation processes is not disclosed.

4. Aim of the research

The aim of the publication is to study the scoop feeder as a means of resource saving in a ball mill during grinding of initial ore with sands of mechanical single-spiral classifier on the basis of application of new models of technological process, a new algorithm for estimation of solid concentration in the pulp of technological unit, control of material flow oscillation and models of water flow rate stabilisation.

In order to achieve the above objective, the following main tasks need to be accomplished:

- consider the ball mill as the main unit for resource saving;
- characterise the scoop feeder as an important means of resource saving;
- review the status of slurry rarefaction stabilisation in ball mills operating in closed cycles with a mechanical single-spiral classifier;
- reveal a distinctive transition in stabilising pulp liquefaction in ball mills;
- outline the essence of an algorithmic method for estimating the solid/liquid ratio for the communications of a ball mill operating in a closed cycle with a mechanical single-spiral classifier;
- investigate the features of implementation of the proposed algorithm for identification of pulp liquefaction in a ball mill operating in a closed cycle with a mechanical single-spiral classifier;
- simulate the conditions of resource saving at grinding of initial ore with sands of mechanical single-spiral classifier.

5. Method

5.1 The ball mill is the main unit for resource saving

Grinding of raw materials at iron ore dressing plants in the first stages is mainly carried out according to the technological scheme, where the ball mill operates in a closed cycle with a mechanical single-spiral classifier. For such technological cycles in [1] the necessary stabilisation at appropriate levels of ball mill loading with ore and pulp density in it is proved. The importance of stabilisation of pulp liquefaction stabilisation in ball mills is also pointed out in [2, 3] and others. That is, only at a certain ore load of the ball mill and specifically necessary liquefaction of the pulp in the drum there will be resource-saving grinding of raw materials. However, these are only the initial conditions for effective grinding. At the entrance of the ball mill at the same time receives dry initial crushed ore, water and sands of mechanical single-spiral classifier, fed by scoop feeder. Although the ball mill is an efficient agitator, the material is not averaged in the initial section of the drum. Such material cannot be effectively pulverised. That is, it must be averaged (mixed) to a uniformly coarse solid state, which will occupy a certain length of the drum - at least one third of it.

With average material, three cases can arise. If there is a lot of solid material, the impact of the balls will not effectively break the raw material – this is overloading the mill and inefficient use of the energy used to lift the balls and the balls themselves, which wear out but do not break the ore well enough. If there is little material, it is underloading the mill with raw material. The ball energy is not fully utilised for breaking, little raw material is broken, and the residual energy is consumed for breaking the grinding body itself and the lining. Consequently, resource saving will only occur at a certain volume of material in the ball working areas and this must be maintained. The material, normally averaged and normally loaded, moves along the drum and is gradually pulverised. At the output, the coarseness must correspond to the set value. Both the required travelling speeds and the coarseness of the solids in the mill discharge can only be achieved at a certain concentration of solids in the pulp, appropriate to the process. This is also stated by the authors of [4].

At the initial section of the drum, irrespective of the optimality of the mill loading with ore, due to the nonconcentration of large pieces of solid, classifier sands and water, zones are created where large pieces are over-concentrated and where their arrangement is almost opposite. This character of the arrangement of the feed ore in the mixture practically excludes the creation of zones with nominal concentration of coarse solids. This corresponds to inefficient ball operating conditions. It is therefore important to effectively mix the material almost from the point of loading.

Material flows - feed ore, water, classifier sands – are characterised by a certain instability, which can excite oscillations of the liquid mixture in the mill drum. This also worsens the conditions for grinding large particles of solid. Fluctuations of the liquid mixture in the drum are determined by the frequency and amplitude at the inlet. With the help of special programmes, computer modelling has established the areas of variation of oscillatory parameters of ore streams and water at the inlet of the technological unit, when the ratio of the mass value of the parameter to the mass of the liquid product in the drum does not exceed 3,0% [5]. It is known that at such deviations, the technological unit does not leave the nominal operating mode. The boundaries of the obtained areas of variation of oscillatory parameters at the input of the technological unit allow us to set limits in the implementation of automatic control of ore grinding. From the considered it can be seen that resource saving in the ball mill is determined by the state of the material in the drum and oscillatory input flows of the initial ore, water and sands of the mechanical single-spiral classifier. The analysis established that it is possible to increase resource saving during grinding of raw materials in a ball mill only through the influence on the input material flows. Studies have shown that the flows of feed ore and water into the drum do not change the technological mode of operation of the ball mill so much that the oscillatory parameters go beyond the established areas. The influence of other factors on the resource efficiency of the mill during the grinding of feed ore should be checked.

5.2 Scoop feeder - a means of resource saving

The scoop feeder is an integral component of the ball mill in this ore grinding cycle. It, in turn, is an integral part of the drum feeder that feeds ore, water and balls into the process unit. The scoop feeder is a spiral-shaped gripping organ, endowed with a round hole in the side wall for reloading the captured at the bottom mark liquid sands of the classifier into the ball mill drum [6]. It includes two spiral-shaped sidewalls, parallel spaced at a certain distance and rigidly fixed on the side of the spiral part by a metal profile bottom, and a flange in the vicinity of the outlet round hole for bolting to the drum trunnion of the technological unit. The scoop feeder has a rectangular cross-section between the sidewalls, which width should be greater than the diameter of the largest ball and sufficient to move the sands at their highest productivity. The body of the feeder's gripping body is cast from alloyed cast iron or made of sheet steel. The inner surface of the gripper is lined with steel plates. A replaceable visor made of manganese steel or alloyed cast iron is installed on the end of the gripping body to protect it from wear. Scoop feeders are made with one, two or three gripping bodies. The scoop feeder rotates together with the mill drum.

Schematic representation of scoop feeder in the technological scheme is shown in Fig.1.

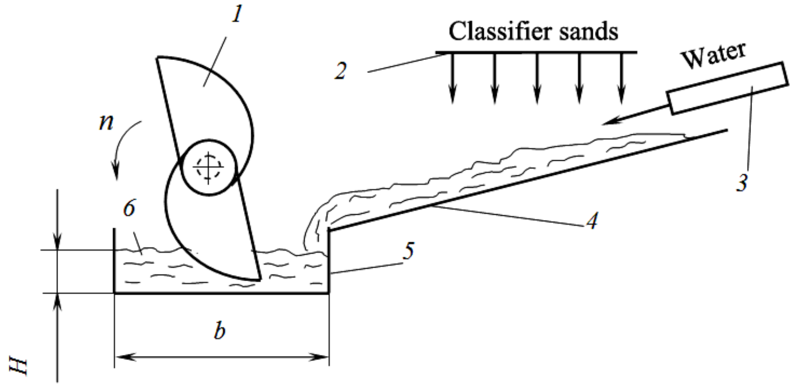

Fig. 1. Schematic representation of the scoop feeder in the process flow diagram: *1* – scoop feeder; *2* – threshold of mechanical single-spiral classifier; *3* – water supply pipeline to the classifier sand chute; *4* – classifier sand chute; *5* – scoop feeder receiving device; *6* – pulp

The scoop feeder *1* rotates together with the mill drum, making *n* revolutions per minute. The sands of the mechanical single-spiral classifier are discharged through the sand sill *2* into the sand chute *4*, where at its beginning water is supplied through pipe *3* to ensure their movement and create a pulp. The pulp *6* contains the hard sands, the water which is discharged from the classifier with them, and the added water from pipe *3*. It is accumulated in the receiving device *5*, which has a length *b*. At any volumetric capacity in the receiving device *5*, certain values of the pulp level *H* are set. That is, in the steady-state mode of operation, the volume of pulp coming from the classifier per unit of time will correspond to the quantity removed from the receiving device *5*. Therefore, the scoop feeder is a kind of transfer link between the mechanical single-spiral classifier and the ball mill.

Scientists have paid little attention to the study of spiral feeders. Therefore, it is necessary to investigate the nature of sand feeding of mechanical single-spiral classifier into the ball mill. We will carry out researches according to the considered approach with attraction of the received diagrams of non-exit of the technological unit from 3% zone of deviations of pulsations of liquid material in the drum. The research was carried out on the real test data of the technological scheme in the conditions of one of the ore dressing plants. Let's take the smallest 163,2 t/h and the largest 329,0 t/h values of circulating load, fixed in experiments [7]. It is established that it is inadmissible to feed the sand stream directly from the classifier into the ball mill, due to large oscillations of the material in the drum of the technological unit. When using a scoop feeder with one gripping element, ore and water pulsations do not leave the zone of 3,0% deviations. The use of a scoop feeder with two gripping elements significantly improves the indicators. So, in terms of pulsations, all material flows into the ball mill meet the process requirements, as the scoop feeder significantly improves the sand flow by converting it.

5.3 Status of stabilisation of pulp liquefaction in the mill

As it has been shown, resource-saving ball milling of initial ore will be carried out if the oscillation of material flows does not exceed the established limits and qualitative averaging of solids by size. However, a necessary condition is still the maintenance of a specific value of solid particle concentration for a certain technological ore type, i.e., in general, at the beginning of the process it is necessary to stabilise the solid/liquid ratio at a given level. The solid/liquid ratio can be set as the ratio of the total flow rate of ore and sands from the classifier (circulating load) to the water flow rate to the ball mill. Water flow rate is measured by a number of known types of flow meters, and the mass flow rate of ore into the ball mill is estimated by conveyor scales with a stated relative error of ±1,0%, which, as it was found in practice is not quite confirmed. Improvements to the conveyor scales outlined in the works [8-10], which guarantee the measurement of ore flow rate into the ball mill with an error somewhat less than 1,0%. Circulating load measurement is more problematic. The development of these techniques has received considerable attention. The most weighty of them are published in the works [11-16]. Devices and methods of estimation of this technological parameter realise various approaches, but it was not possible to achieve the necessary accuracy.

When measuring the circulating load, the accuracy was mainly influenced by the flow dynamics. The static sand conditions are maintained in the classifier spirals, where the sands do not pulsate, but only gradually move towards the sand threshold. Therefore, attention was drawn to this feature of sand condition and subsequently started to carry out research in this part of the process flow diagram. Ways to evaluate the performance of spiral classifier on sands were proposed [17-19]. Since these methods had disadvantages, such studies were subsequently continued. Improved methods for determining the performance of spiral classifier on sands were proposed [20-22], but the disadvantages of previous approaches could not be completely eliminated and these technical solutions, containing elements of assumptions, also gave an error, which does not quite meet the requirements of the technological process. This forced researchers to develop solid/liquid stabilisation systems.

A group of researchers (V.I. Dmitriev and others) proposed three systems of automatic control of the solid/liquid ratio in closed cycles of initial ore grinding [23-25]. These systems are very different from each other, so let us consider them separately.

Among the disadvantages of the system of automatic control of the ratio of liquid and solid phase flow rates in the mill feed with setting the necessary averaging time intervals and data delay [23] are the following. Firstly, significant errors are allowed when determining the solid and liquid flow rates. The system contains a large number of computational blocks – converters, adders, comparison blocks, which also introduce error. Secondly, measuring pulp density at the mill drain is currently not technically feasible. In addition, there is a significant delay in signal acquisition. Thirdly, the determination of the solid/liquid ratio from the measured value of the pulp density and other parameters also introduces additional error. Fourthly, the scheme proposes to use an experimental delay time which cannot be set accurately – different situations will have different delay intervals, so it is not practically possible to apply this approach of stabilising the solid/liquid ratio under these conditions.

The system of automatic regulation of the ratio of solid and liquid phase flow rates in the mill feed with preliminary determination of the optimum value of pulp density [24] also has certain drawbacks. In particular, the solid flow rate is determined with a large error, since the flow rate of sands cannot be accurately measured. Also, the system involves the use of many elements that introduce additional errors - these are adders, moisture content determination unit, ratio determination unit.

Finally, let us consider a system of automatic control of the ratio of the flow rate of inlet streams into the mill with determination of the total mass flow rate of solid phase and water [25]. It is characterised by shortcomings of technical nature. This concerns the impossibility of measuring the mass flow rate of pulp in open streams at high values of densities due to the lack of such means. Existing devices for mass flow rate determination are not suitable for such measurements [26]. Also, there are no means of measuring sand density today. The system is overloaded with a large number of parameter determination blocks, which introduces a significant additional error.

Therefore, several approaches to create automatic systems for stabilising the solid/liquid ratio for closed cycles of ball milling of initial ore with classifier sands have been proposed; however, as the analysis has shown, none of them can be implemented for various reasons. Therefore, the search for approaches to overcome this technical contradiction should be continued.

5.4 Excellent approach in stabilising pulp liquefaction

Let's consider the device for automatic control of loading and stabilisation of pulp liquefaction in the mill in accordance with the copyright certificate [27] №388790 (USSR) and Fig. 2. The sands of the classifier by spiral *11* are discharged into the sand chute *1*, where water is fed through pipeline *2*, creating a pulp. The pulp, moving in the sand chute *1* falls into the accumulating tank *10* and further - into the pulp outlet *9*, and then - into the receiving device *8* of the scoop feeder. The volumetric flow meter *7* measures the pulp flow rate $Q_{\upsilon n}$ in the sand chute *1*, and the flow meter *6* measures the water flow rate Q_{B1} into the sand chute. Their signals are fed to the input of the computing device *6*, which determines the ore flow rate Q_{qp} according to the equation

$$Q_{qp} = \frac{\delta_T}{1 + k_P \frac{\delta_T}{\delta_B}} \left(Q_{\upsilon n} - Q_{B1} \right) = A \left(Q_{\upsilon n} - Q_{B1} \right), \qquad (1)$$

where δ_T, δ_B - ore and water densities, respectively; k_P - moisture content of classifier sands; A - constant for a certain technological ore type.

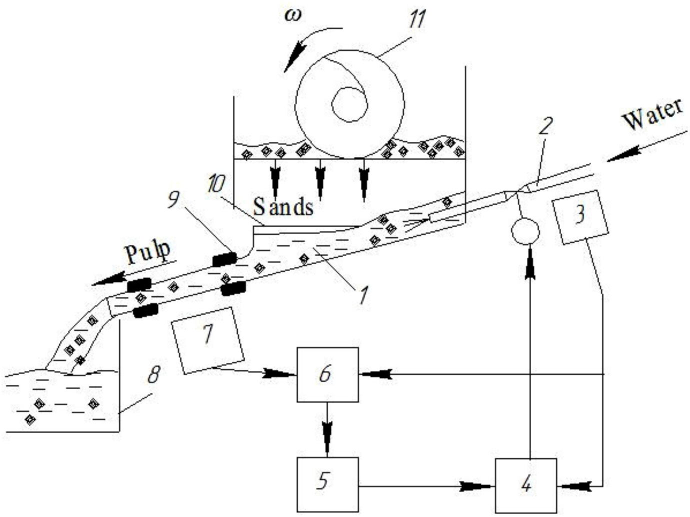

Fig.2. Device for automatic control of loading and stabilisation of pulp liquefaction in the mill: *1* - classifier sand chute; 2 - pipeline; *3* - water flow meter; *4* - ore and water feed ratio regulator; 5 - device showing the amount of material loaded into the mill; *6* - computing device; *7* - pulp volume flow meter; *8* - scoop feeder receiving device; *9* - pulp outlet; *10* - accumulating tank; *11* - classifier spiral

The signal formed at the output of the computing device *6* is measured by the device *8*, which shows the value of the mass flow rate of ore Q_{qp} into the mill. This signal and the flow meter signal are fed to the input of the ratio regulator *4*, which by adjusting the water flow rate Q_{B1} maintains constant pulp liquefaction in the mill.

The accuracy of the control is determined by the accuracy of the slurry and water flow meters. If the pulp outlet is well filled with liquid, it is possible to measure the volume flow rate of the pulp with sufficient accuracy. The water flow rate can be measured with standard devices. The wiring diagram of the device is simple and practically accommodates standard devices that provide the required accuracy in industrial applications.

The distinctive feature of this approach is that instead of a mass flow meter, a device that measures the pulp volume flow rate in the classifier sand chute is used. The slurry flowmeter with an accumulating tank has proven to be a good solution, but requires complex measures to protect it from scrap and other foreign objects. In addition, it is characterised by significant metal consumption, complexity of installation. Subsequently, a solution was found to estimate the volume flow rate of pulp in the sand chute by scanning its surface [28]. It is shown that it is expedient to scan open surfaces of streams by devices realising the method of measuring surface coordinates by rays of constant length, which change their position in space. Their length should be several times greater than the maximum flow height. The control of the flow height should be carried out at four points along its width - at a distance of 0,1 and 0,4 from the edges. This provides the highest accuracy of cross-sectional area measurement. However, the check showed that the relative error of pulp volume flow measurement can be within 3-5%, which requires further search.

5.5 Algorithmic method for pulp liquefaction identification

Adaptive methods based on the invariance principle are used to improve the measurement accuracy of individual parameters. Recently, the algorithmic method of increasing the measurement accuracy has been developed, which is also based on the invariant principle, where the measured value is determined in the computing device in accordance with the developed algorithm. When creating automatic control systems, the expediency of incomplete satisfaction of invariance conditions has long been recognised. This allows to apply the algorithmic method of increasing the accuracy of parameter determination directly in the identification process, if the problem can be reduced to an algorithm of the necessary type. It is proved that the algorithmic method can, under certain conditions, provide the necessary accuracy of estimation of the technological parameter when measuring one of the values with a significant error.

For the communications of a ball mill operating in closed loop with a mechanical single-spiral classifier, the following algorithm has been formulated

$$K_{T/P} = \frac{A \cdot (Q_n - Q_{B1}) + Q_p}{\delta_B Q_B + \delta_B Q_{B1} + K_n [A \cdot (Q_n - Q_{B1})]}, \tag{2}$$

where

$$A = \frac{\delta_T}{\left(1 + K_n \dfrac{\delta_T}{\delta_B}\right)} = \frac{\delta_T \delta_B}{\delta_B + K_n \delta_T}, \tag{3}$$

K_n – relative moisture content in classifier sands; Q_n – volume flow rate of pulp in the classifier sand chute; Q_{B1} – volume flow rate of water into the sand chute; Q_B - volume flow rate of water into the ball mill; Q_P – mass flow rate of ore into the ball mill.

Algorithm (2) shows that its expression includes the parameter Q_n – volume flow rate of pulp in the sand chute of the classifier, which is estimated with a significant error. There is also a mechanism to compensate for the error in determining this parameter, since Q_n is included in both the numerator and denominator of the expression. To identify the solid/liquid $K_{T/P}$ ratio, it is necessary to have information on the pulp volume flow rates Q_n in the classifier sand chute, ore mass flow rate to the ball mill, water flow rate Q_B to the ball mill, water flow rate Q_{B1} to the sand chute, moisture content of the classifier sands K_n and ore density δ_T. The final identification result will be affected by the errors in the determination of each of these parameters.

Let us consider the influence of parameter determination errors in algorithm (2) on the accuracy of predicting the solid/liquid $K_{T/P}$ ratio. Let us introduce the concept of the base value $K_{(T/P)B}$, which is determined at parameter values without error. In this case, it is equal to $K_{(T/P)B}$=4,3. If any of the six parameters (δ_T, K_n, Q_{B1}, Q_n, Q_P, Q_B) does not correspond to the base value, the solid/liquid ratio according to algorithm (2) will be predicted with error. At computer modelling of the given process dependences of a relative error of prediction of a ratio solid/liquid on algorithm (2) from a relative error of definition of one of parameters for the case when the last corresponds to base value (fig.3) are received. The dependences of Fig. 3 show that algorithm (2) has the property of error compensation for all six parameters, but the degree of compensation for each of them is different. The greatest influence on the $K_{T/P}$ prediction error is the accuracy of measurement of water flow rate into the mill, the least - the ore density. At a certain direction of measurement error deviation, three parameters in the result of $K_{T/P}$ prediction contribute negative error, and three - positive error. All these factors in pairs contribute almost the same influence on $K_{T/P}$ with opposite signs.

It is also evident from the graphs in Fig. 3 that all parameters introduce a certain error when predicting the solid/liquid ratio in the mill. Without taking special measures, the resulting error in predicting the solid/liquid ratio in the mill can be quite high. Therefore, it is necessary to make a more detailed analysis of the influence of parameter measurement errors on the result of the $K_{T/P}$ identification.

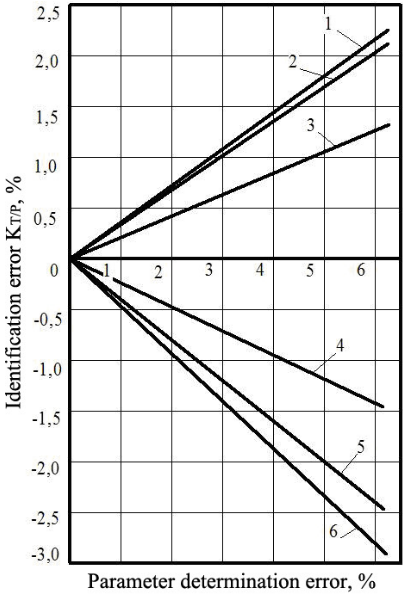

Fig.3. Dependence of the relative error of predicting the solid/liquid ratio in the mill on the error of determining one of the parameters:
1 - Q_P; 2 - Q_n; 3 - δ_T; 4 - *Q_{B1}; 5 - K_n; 6 - Q_B*

5.6 Features of the implementation of the proposed algorithm

It is clear that at each moment of time the error of measurement or deviation of this or that technological parameter from the prescribed value can take the sign "plus" or "minus". This will be a random process. Since the sign of the parameter determination error affects the resulting solid/liquid ratio error differently, $\delta_{KT/P}$ will also be a random process. However, it is possible to set limits to the variation of the relative solid/liquid ratio error in this process. The limiting value of the resulting error of the solid/liquid ratio will be at the unlikely situation - when all errors of measurement of technological parameters take the same sign. The second unlikely situation corresponds to another limiting condition. It will take place when the measurement errors take different signs and the most unfavourable combination of them.

If all process parameters are measured with the same errors, which have the same sign, then even with a relative error of 5%, the relative error in determining the solid/liquid ratio does not exceed 1,1%. This would be the lower limit of the parameter identification error. This error can be practically halved if in the technological process the moisture content of the classifier sands, ore density and water flow rate into the sand chute are unchanged and precisely set.

If all technological parameters are measured with the same errors, and their signs take the most unfavourable combination, the resulting error of identification of the solid/liquid ratio increases significantly. When measuring technological parameters, for example, with the same error of 5%, the resulting error of identification of solid/liquid ratio will be more than 10%. It can be significantly reduced provided that the values of classifier sands moisture content, ore density and water flow rate into the classifier sand chute are constant and highly accurate. This will be the upper (theoretical) limit of the prediction error of the solid/liquid ratio in the ball mill, as it cannot really exist even in unlikely situations due to the much higher accuracy of most existing measuring instruments.

The actual prediction error of the $K_{T/P}$ parameter will be somewhere between certain limits, since the real situation of measuring process parameters is unlikely to approach the limiting conditions. Such actual error should satisfy the requirements of the technological process.

Thus, it follows from the analysis that when implementing algorithm (2), it is desirable to ensure that the moisture content of the classifier sands, ore density and water flow rate into the classifier sand chute remain constant. At present, it has been concluded that it is expedient to process separate technological ore types in separate technological complexes [29]. Under these conditions, the ore density will be unchanged, and the moisture content of the classifier sands will also be constant [30]. In process schemes where the ball mill operates in a closed cycle with a mechanical single-spiral classifier, it is possible to maintain the conditions of supplying a constant water flow rate into the sand chute [31]. The authors of this publication have developed approaches and a means of stabilising the water flow rate into the sand chute of the classifier, which ensures a dosing error of less than 1% [32-34]. Therefore, it is necessary to ensure a sufficiently high accuracy of measuring the mass flow rate of ore in the mill, water into the mill with a relatively inaccurate flow meter of pulp volume flow rate in the sand chute of the classifier. The best results of predicting the solid/liquid $K_{T/P}$ ratio by the algorithm (2) can be obtained on the basis of optimisation of the choice of measuring instruments by their permissible error. Table 1 shows the absolute errors of identification of the solid/liquid ratio in the mill at the accepted values of parameters in dependence (2), arising under the influence of water flow measurement with a certain relative error. It follows from the data of Table 1 that the absolute error of $K_{T/P}$ prediction increases with increasing relative error of ore flow measurement. The best results will be at the lowest measurement error. In the process of optimisation it was established that the ore flow meter, water flow meters to the mill and sand chute should have a measurement error of ±1%, and the pulp flow meter – ±(3...5)% with the error of the ore density and moisture content in the classifier sands ±1% [35]. With such means, the solid/liquid ratio identification errors are 0,951% for a pulp flow meter error of ±3% and – 1,626% for a pulp flow meter error of ±5%. It is possible to provide the mill water flow rate with standard instruments and the ore flow rate with advanced conveyor scales [8-10].

Table 1

Absolute errors in predicting the solid/liquid ratio in the mill when varying parameters are measured with different uncertainties

Variable parameter	Relative errors of measurement of varying parameters, %				
	1	2	3	4	5
Ore flow to the mill	**0,01580**	0,03159	0,04730	0,06321	0,07912
Water flow to the mill	**-0,02069**	-0,04110	-0,06106	-0,08084	-0,10105
Pulp flow rate in the sand chute	0,01520	0,03038	**0,04515**	0,06020	0,07482

5.7 Conditions for resource saving during ore grinding

To obtain the above results of solid/liquid ratio prediction according to algorithm (2) is possible, moreover, if all process parameters are measured at the same process point, i.e. when the process is not affected by different lags. Delays can be influenced in the ore feed, water to the mill, pulp and water to the sand chute of the classifier. If the classifier sand chute is fed with a constant water flow rate, there is no lag in this channel. If the pulp volume flow rate is measured at the end of the sand chute, this information regarding the material flow entering the ball mill will be lagged by the lag time in the scoop feeder, which is constant and is determined by its design and operating characteristics. That is, the scoop feeder in the technological communications of the ball mill is a key element, as it guarantees the conditions of equalisation of the lag in all channels of the material flow into the ball mill. To exclude the influence of lag on the result of $K_{T/P}$ prediction by algorithm (2) it is necessary to equate the lag time in the ore and water supply lines to the mill with the value of the parameter in the scoop feeder. This can easily be done by installing conveyor scales at a certain point or by selecting the belt speed and choosing the length and slope of the chute feeding water to the mill.

Therefore, the prerequisites for ensuring the necessary concentration of solid in the ball mill slurry have been considered, but to achieve resource saving in the ball mill when grinding the initial ore with sands of a single-spiral classifier, it is still necessary to ensure the inclusion of the initial section of the mill drum in active operation. The analysis has shown that this can be realised only by influencing the ore and sand flows into the mill [36]. That is, as the analysis has shown, the total water flow rate into the ball mill, determining the given solid/liquid ratio, should be divided into three unequal streams, the first of which is fed directly to the ore directed to the technological unit, automatically changing the amount of liquid according to the solid surface flow rate in the ore stream, multiplied by the thickness of the water film held by molecular adhesion forces, with the determination of the regulated value according to the dependency

$$Q_{PB} = \frac{6\alpha_P}{L_\delta^2 \delta_T^2} \cdot \frac{P_L^2 \cdot \upsilon \cdot \Delta n}{S_{pn}}, \tag{4}$$

second - according to the flow rate of added water at the inlet of the scoop feeder receiving device, which is possible due to its unchanged lag time, with its calculation according to the equation

$$Q_{BD} = \frac{Q_n - Q_{B1}}{\left(\frac{\delta_B}{\delta_T} + K_n\right)} \cdot \left(\frac{1}{K_{(T/P)G}} - K_n\right) - Q_{B1} \quad (5)$$

third - in accordance with the condition $Q_{DBM}=Q_{BM}-Q_{PB}-Q_{BD}$
where α_P is a constant characterising the ore loosening during destruction; L_δ is the base distance on conveyor scales; P_L is the ore mass measured by conveyor scales at the base distance L_δ; v is the conveyor line speed; S_{pn} is the cross-sectional area of the ore stream; K_n is a constant characterising the moisture content in the classifier sands; $K_{(T/P)G}$ is the limiting value of the solid/liquid ratio in the pulp of the scoop feeder receiving device; Δn is the thickness of water film held on the surface of ore pieces by molecular adhesion forces; Q_n is the volume flow rate of pulp in the classifier sand chute; Q_{B1} is the volume flow rate of water supplied to the sand chute; Q_{PB} is the volume flow rate of water proportional to the surface of ore pieces; Q_{BD} is the volume flow rate of water added to the mill; Q_{BM} is the total volume flow rate of water to the mill.

These effects of water on the material flows in the ball mill prepare them for rapid penetration into each other and active mixing from the very beginning of the drum through its rotation, the movement of the balls and the entire material along the inclined surface. In this section, the active grinding of solids in a resource-efficient manner begins immediately.

6. Conclusions

The conducted research allows us to draw the following conclusions:

1. It is established that resource-saving grinding of raw materials will occur only at a certain ore loading of the ball mill and specifically necessary liquefaction of pulp in the drum. Despite the fact that the ball mill is an efficient agitator, the material is not averaged in the initial section up to 1/3 of the drum length and is therefore poorly pulverised. Resource saving will only be achieved with a certain volume of material in the ball areas and this volume must be maintained. Both the required travelling speed and the required solid size in the mill discharge can only be achieved with a certain concentration of solids in the pulp, which is appropriate for the process. Fluc-

tuations of the liquid mixture in the drum are determined by the frequency and amplitude at the inlet. They must be such that the process unit does not leave the nominal operating mode. Resource conservation in a ball mill is determined by the state of the material in the drum and the oscillating inlet streams. Flows of initial ore and water into the drum do not appreciably change the technological mode of the ball mill. To increase the resource saving during the grinding of raw materials in the ball mill is possible only through the influence on the input material flows.

2. A scoop feeder is a spiral shaped gripper for transferring the classifier liquid sands captured at the bottom mark into the ball mill drum. Scoop feeders are used with one, two or three gripping bodies. The scoop feeder rotates together with the mill drum. In steady state operation, the volume of pulp coming from the classifier per unit time will correspond to the quantity removed from the intake. So far, scientists have paid little study to scoop feeders. It has been established that directly from the classifier the sand flow into the ball mill is inadmissible due to large oscillations of the material in the drum. When using a scoop feeder with one gripper, the ore and water pulsations do not exceed the 3% deviation zone. The performance is significantly improved by a scoop feeder with two grippers. Consequently, since the scoop feeder significantly improves the sand flow by converting it, all material flows to the ball mill meet the process requirements in terms of pulsations.

3. Several approaches for creating automated systems for stabilising the solid/liquid ratio for closed cycles of ball milling of initial ore with classifier sands have been proposed, but, as the analysis has shown, none of them can be implemented for various reasons. Therefore, the search for approaches to overcome the technical contradiction should be continued.

4. A mathematical model of a device for stabilising pulp liquefaction in a ball mill is proposed, the distinguishing feature of which is the use of a volumetric pulp flow meter in a sand chute instead of a mass flow meter. A solution for estimating the volumetric flow rate of pulp in the sand chute of a classifier by scanning the flow surface is found. The relative error of pulp volume flow rate measurement is within 3...5%, which requires further search.

5. A solid/liquid ratio prediction algorithm is proposed for the communications of a ball mill operating in a closed loop with a mechanical single-spiral classifier, which includes the densities of water and ore, the relative moisture content of the classifier sands, the volume flow rate of pulp in the classifier sand chute, the volume flow rate of water into the ball mill and sand chute, and the mass flow rate of ore into the ball mill.

It is shown that this algorithm has the property of error compensation for all parameters, but the degree of compensation for each parameter is different. Therefore, without special measures, the resulting error in predicting the solid/liquid ratio in the mill can be quite high.

6. It is established that the limiting errors of estimating the solid/liquid ratio when measuring all parameters in the algorithm with an error of ±5% will be within 1,1%-10%.

If in the technological process the moisture content of the classifier sands, ore density and water flow rate into the sand chute will be unchanged and accurate, then the specified errors are halved, which is easily possible to realise, since the moisture content of the sands is unchanged and ore density is unchanged when processing one technological different types of ore, and the developed water flow meter into the sand chute provides a small error, which is less than 1%.

Therefore, it is necessary to ensure a sufficiently high accuracy of measurement of the mass flow rate of ore into the mill, water into the mill with a relatively inaccurate flow meter of pulp volume flow rate in the sand chute of the classifier. In the process of optimisation it was established that the ore flowmeter, water flowmeter into the mill and sand chute should have a measurement error of ±1%, and the pulp flowmeter – ±(3-5%) with the error of the ore density and moisture content in the sands of the classifier ±1%. With these means, the solid/liquid ratio identification error is 0,951% with the slurry flowmeter error of ±3% and - 1,626% with the slurry flowmeter error of ±5%.

7. It is possible to obtain high accuracy of solid/liquid ratio estimation only under conditions of equal or no lag in all material flows. Using the invariability of the lag in the scoop feeder and the non-variability of the water supply conditions (stabilisation) in the classifier sand chute, this problem can be solved by selecting the mode of ore flow measurement by conveyor scales and water supply to the ball mill.

8. To include the initial section of the ball mill in active grinding with resource saving, three mathematical models of water flow rate into the ball mill have been developed - to the feed ore, into the scoop feeder receiving device and directly into the ball mill.

9. All this provides resource-saving grinding of ore with sands of mechanical single-spiral classifier with saving of consumption of electric energy, balls and lining and increase of productivity of ball mill and reduction of losses of useful component.

The direction of further research is the development of a system of adaptive distributed resource-saving control of grinding of initial ore with sands of mechanical single-spiral classifier in the first stages of ore preparation.

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