Intelligent optimal control of crushing process of solid materials

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Abstract. Information about the intelligent method of direct optimal control and the method of system thinking in computer modeling of crushing process is given, which shows four hierarchical structures in the analysis of the control object, i.e. crusher. Computer models of the processes in the crusher are built starting the analysis from a sub-object of a deep hierarchical level that is a piece of material. The computer model introduced into the microprocessor allows determining the required calculated concentration of the crushed product and offering automated system for intelligent control of the crushing process of solid materials.

1. Introduction
Grinding processes are widely used in human production activities and in the national economy. Nowadays, more than two billion tons of minerals are crushed and grinded annually in the world, and in terms of the number of employed people, industries using crushing and grinding of mineral raw materials are in second place, second only to agriculture.

The grinding process is accompanied by a decrease in the particle size and a multiple increase in the surface of the crushed material, which allows dramatically improving the quality of materials and products obtained from the crushed material [1-4].

In industry, in most cases, high grinding degrees are required. Sometimes the size of the pieces of the starting material reaches 1500 mm, while in technological processes, sometimes material is used, the particle size of which is fractions of a micron. Such degrees of grinding are achieved when grinding in several stages, since it is not possible to obtain a product of a given final size in one-step (on one machine). According to their purpose, grinding machines are conventionally divided into crushers for large, medium and fine crushing and mills for fine and ultrafine crushing [3, 4, 8-10].

About solid material crushing and crushers
The main machines are classified into the following [3, 4]: jaw crushers, cone crushers, hammer crushers, pulping machines, and roller and ball mills. All crushing machines have general requirements for minimizing dust generation, continuous and automatic unloading, the ability to regulate the degree of crushing, the uniformity of the parts of the crushed material, and low energy consumption per unit of production. The difficulty in regulating the degree of grinding consists in determining the degree of grinding, concentration and dispersion of the ground product. Each crusher design has an optimum crushing ratio for maximum performance. When a high degree of grinding is required, crushing is
carried out in several stages, i.e. a number of crushing machines, different in design and technical characteristics, are sequentially installed [3, 8].

The purpose of this work is to develop an intelligent microprocessor-based determination of the degree of grinding, concentration and fineness of the crushed product by constructing computer modeling of the object of a cone grinder by means of system thinking and the method of multi-stage analysis.

We have considered the development and concretization of the concepts of systems thinking, systems approach, system analysis and multi-stage analysis in modeling the object of a cone grinder and determined their sequence and interrelation of processes. In addition, the concept of systems thinking is brought to the fore. An explanation and clarification of the approach to systems thinking, systemic and multistage analysis is given. Methods of system thinking, analysis, modeling and search for optimal solutions for crusher control are recommended [5-7].

By using multistage system analysis, we have established general patterns in modeling the grinding process of the target product and identified the main interrelationships of effects and phenomena that are important in the grinding process with simultaneous grinding of the target product in the crusher.

The development of the theoretical foundations of the grinding process of the target product in the grinder by means of mathematical modeling of the considered class of processes predetermines the further development of practical techniques and allows the development of methods for the engineering calculation of the studied grinding process in the grinder.

The main object of direct optimal control is a crusher-grinding device. At the first stage of the multistage system analysis [7] the installation, then the grinding device is divided into a number of quasi-devices. These are the crusher body, crushing elements and solid material. In turn, a solid material consists of particles of the first, second, third, etc. size of the crushed target product.

The input parameters of the object in modeling the object of the cone grinder of the target product are: the consumption of solid material $G_0$, the concentration of the crushed target product at the input $C_0$, the size of solid particles $\delta^1$, the energy consumption $N$. Output parameters: material consumption $G_1$, concentration of investigated components at the outlet $C_1$.

The crusher is supplied with material with a certain concentration of particles and dispersion of the crushed product. The material balance equation for the selected component has been compiled (for example, for particles in the grinder $a_1$):

To form a computer model of the grinding process, the record based on precise indicators in the form of a cybernetic system is considered.

\[ C_0 \rightarrow G_1 \rightarrow C_1 \]

energy supplied $N$

**Figure 1.** Structural view of the object.

The input parameters of the system include $G_0$, $C_0$ - material consumption and concentration. Output parameters include $G_1$, $C_1$ - consumption and concentration of particulate matter.

Mathematical modeling of a process in terms of the dynamic structure of the flow structure can be in several variants.

It is possible to write a mathematical explanation of the equation of continuous operation of the system. The material balance of the continuous operation of the crusher can be written as the dynamic equation of the process as follows:
The increasing consumption of the crushed product is as follows:
\[ q_s = KVC_A \]  
\[ (2) \]

The mass fraction of the crushed product concentration is as follows:
\[ C_A = 1 - C \]  
\[ (3) \]

The mass of the crushed product is as follows:
\[ m = m_0C \]  
\[ (4) \]

where, \( m \) – mass, \( G_0 \) – consumption, \( C_0 \) – concentration of the resulting product, \( q_u \) – an indicator that moves the crushed matter, which increases from time to time. In a continuous process, it depends on the coefficient of crushing, the volume of the substance in the device and the concentration of \( C_A \) - the substance coming to the crushing. The crushing coefficient (K) depends on many parameters. Its unit is kg/m³ sec.

The mass of the crushed substance is characterized by the total mass in the device. The concentration of particulate matter is characterized by total consumption.
\[ C = \frac{G_c}{G_1} \]  
\[ (5) \]

Assuming that the mass of the substance in the device does not change, the received (incoming) consumption is equal to the outgoing consumption
\[ G_1 = G_0 \]  
\[ (6) \]

then,
\[ C = \frac{G_c}{G_0} \]  
\[ (7) \]

Taking all this into account for the dynamic characteristics of the process in the crusher, then our equation (6) has the following form:
\[ \frac{dC}{d\tau} = \frac{1}{m_0} \left[ G_0C_0 - G_1C - KV(1-C) \right] \]  
\[ (8) \]

For example, the mathematical model of the product crushing process in a single-stage mill is explained by the following equation:
\[ \frac{dm_0C_0}{d\tau} = G_0C_0 - G_1C_1 + k(1-C_1) \]  
\[ (9) \]

where: \( G_0 \) – consumption of raw materials coming to the mill; \( C_0 \) – concentration of raw materials coming to the mill; \( G_1 \) – consumption of raw materials leaving the mill; \( C_1 \) – concentration of the product leaving the mill; \( k \) – coefficient related to the mill.

Coefficient “k” depends on the flow rate and temperature of gas and material, thickness and porosity of the crushed layer, particle diameter, density, dimensions of the device, etc.
Using the mathematical description of a single-cell continuous process, one quasi-device computer model was obtained using the MATLAB program (figure 2).

\[ k = f (G_g, T_g, T_m, h_{ps}, \rho; \) \]

Figure 2. Computer model of the dynamics for the process of the object of the cone grinder of the target product in the first conical part of the grinder in the MATLAB software.

A calculation algorithm is developed (figure 3) and a computer model is constructed to represent the input parameters of the dynamics of the grinding process in the MATLAB application program.

Figure 3. Computer model for inputting the initial process data into the microprocessor of direct optimal control of the grinder.

The following input parameters are entered into the block for entering computer models: the total mass of the material \( m_0 \), the concentration factor \( k \) and the initial concentration of the crushed component \( C_0 \), \( V \) is the volume of the working zone. The output parameter is the change in the concentration of the crushed component in the general mixture \( C_q \).

The computer model works as follows: after entering the numerical values of the input parameters through blocks 1 and 2, these signals are collected in the signal acquisition unit 3, and then the parameter values are calculated in block 4 and in the integrator 5, the calculation results are displayed in the form of time graphs 6. The obtained results are repeat fed to the signal collection unit, and determined in the calculation unit 9. The calculation results can be observed on the digital screen 7 and in the form of time graphs in the device 6.

The result of calculating one of the variants of the dynamics of the process in the crusher in the MATLAB application program is shown in figure 4.
Figure 4. Result of calculating one variant of the dynamics of the device process on the computer model of the device in the MATLAB software.

We can select a multi-cell model for the flow structure in the device to suit the crushing mode.

A multi-cell quasi-device model is used to model a continuous grinding process. The flow structure in the cell of each quasi-device is assumed the ideal mix.

The system is made up of specific sections, and an equation is created for each section of the process. Mixing of material occurs in each plot. Using the MATLAB program, a mathematical model of continuous grinding was developed for ideal fractionation quasi-device consisting of several grains. The following equation is formed for the process in the selected quasi-device:

\[
\frac{dc_q}{dz} = \frac{1}{m_q}\left(G_{q-1} \cdot C_{q-1} - G_q \cdot C_q - kV(1 - C_q)\right)
\]

(11)

\[
K = f(W_1 \cdot P_1 \cdot \delta_1 \cdot \ldots);
\]

\[
V = \frac{m_2}{P}; \quad m_2 = V \ast p
\]

Here we can determine the number of zones required to obtain a given concentration of crushed material by solving the model.

Thus, by calculating the mathematical model of the grinding process, we can determine the characteristics of the grinder and the optimal performance of the process. With these indicators, we can determine the optimal apparatus.

where, \(G0\) – the consumption of raw materials coming to the mill; \(C0\) – the concentration of product coming to the mill; \(G1\) - consumption of product leaving the mill; \(C1\) – the concentration of product leaving the mill; \(k\) – the coefficient related to the mill.

Thus, by calculating the mathematical model of the grinding process, we can determine the dynamic characteristics of the crusher and the optimal performance of the process. With this, we can achieve optimal control of intelligently open crusher.

The crusher consists of concrete sections - quasi-device, and the equation for each quasi-device of the process is formed. Grinding of material occurs in each plot. Using the MATLAB program, a mathematical model of continuous grinding for ideal grinding quasi-machines consisting of several quasi-machines was developed. The following equation is formed for the process in the selected quasi-device:

\[
\frac{dc_q}{d\tau} = \frac{1}{m_q/n}\left(G_{q-1} \cdot C_{q-1} - G_q \cdot C_q + kV(1 - C_q)/n\right)
\]

(12)

\[
V = \frac{m_2}{P}; \quad m_2 = V \ast p
\]
\[ K = f(W_1 \cdot P_1 \cdot \delta_1 \cdot \ldots) \]

By this, we can determine the number of quasi-devices required to obtain a given concentration of pulverized grinded material by solving the model.

Figure 5. Computer model of the dynamics of the whole process of multi-quasi-device crushing in the MATLAB software.

The result of calculating one of the variants of the dynamics of the process of multi-quasi-device crushing in the MATLAB application program is shown in figure 6.

Figure 6. Result of calculating one variant of the dynamics of the general process of multi-quasi-device crushing on a computer model of the device in the MATLAB software.

As seen from figure 6, after starting the crusher, the curves are shown from bottom to top, the concentration of the crushed product in the quasi-devices of the open loop optimal control increases from the initial zero value to the established approximate value.

The concentration of the crushed product from the last quasi-device being the control parameter will be calculated by the microprocessor of the intelligent control system. Because of the computer model, an automated system for intelligent control of the product-crushing object is developed.

2. Conclusion
Method of construction a model and intelligent control of the crushing process based on the combination of models of processes in quasi-crushers is shown. The studies carried out on a computer model show that the concentration of the crushed product in the quasi-device of the open loop optimal control increases from the initial zero value to the steady-state approximate value. The computer model of the crushing process and the program for calculating the crushing process introduced into the microprocessor allows offering the automated system for intelligent control of the product-crushing object.
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