Mathematical model of glass crushing in the jet mill

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Abstract. Environmental management and environmental protection require waste recycling and industrial circulation of substances that does not violate the ecological balance and will be beneficial for the national economy. Thus, the development of a non-waste technology for glass production, research on recycling, industrial glass production waste and optimization of technological regimes for glass production waste processing are promising for manufacturing marketable products.

1. Introduction
As a micaex binder, special low-melting glass is used. The glass should wet mica and interact with it at a temperature lower than the temperature of mica destruction. It should ensure resisting effects of chemicals, water, aggressive media, have high electrical characteristics when heated, form a melt capable of bonding the composite during the pressing process.

Micalex has been used for 50 years. Glass was developed at Leningrad Technological Institute. Initially, boron-lead glass was used for the production of micalex but the method was abandoned due to the harmfulness of lead oxide, scarce raw materials and large specific gravity of the product. [1]

The development of lead-free glass began with the study of boron-zinc glasses. The study showed that their softening temperature is higher than that of boron-lead glass. The softening temperature of glass was reduced by introducing alkaline oxides. [2]

Using this glass, quality micalex samples were produced, but this glass had a too short softening temperature range and dissolves mica with increasing temperatures. Micalex with an insufficient mechanical strength was produced. When heated, mica is not melted by glass and the micalex is porous. [3] Silica was introduced to change the glass composition. The study showed that boron-lead glass can be replaced by lead-free glass. By means of the systematic changes in the composition, glass 20 was obtained; it was used for the production of micalex from 1939 to 1940 [4]. On the basis of glass 20, glass 203 was obtained [5]. This glass contains a small amount of acidic oxides. At 700 °C, spreadability is 50-55 mm. Given the deficiency of barium oxide, the research aimed to reduce this component in the micalex was carried out. Glass 25 was produced. But the studies were carried out only in laboratory conditions, since this glass contains a strategic deficient component titanium oxide.

Researchers of Riga and Irkutsk Polytechnic Institutes have produced glass designed to increase the electrical insulation properties at high temperatures [6].

That glass was not used as it contained harmful fluorine compounds. To increase the heat resistance of micalex, the Moscow GIS researchers produced glass types 2, 12, and 14. [7]. Studies were conducted on mica wetting with these types of glass and the following conclusions were obtained: glass types 2, 12, 14 wet mica at the limit of its heat resistance or beyond its upper limit; therefore,
they are not suitable as glass bonds. The beginning of wetting with glass 15 occurs at a temperature much lower than the temperature of the above glass type [8]. Industrial testing showed that at a hot pressing temperature of 470 °C, using glass 15, one can produce well-pressed monolithic plates of micalex. Glass 15 is better than glass 203 as it contains no harmful impurities like fluorine and deficient ones like barium oxide. According to [8], high dielectric and mechanical parameters of the composition containing glass 15 proved its advantage compared to glass 203. However, the use of micalex containing glass 15 as an insulating material is limited due to insufficient insulating properties, especially at high temperatures [8].

2. Materials and methods

The material was grinded in a crushing chamber of the jet mill where the compressed air was supplied. Through the nozzles, the crushing stream enters the crushing chamber, where it forms an aerosol of glass - a fluidized layer. Around jets of crushing air, there is an intensive circulation of particles. Typical velocities of the crushing air streams entering the fluidized layer are 400-700 m/s. The crushing stream is supersonic which causes a complex local dynamics of particle acceleration by air and the distribution of the substance in jets. When the air stream enters the fluidized layer, glass is drawn into the stream and accelerated up to a flow rate. During the involvement of glass particles in the flow, particles collide with each other. Such collisions are due to different velocities and sizes of particles and different entry points to the stream. 70% of the material are crushed in the zone where particles enter the aerosol; the remaining 30% are crushed when it encounters, changes the direction, or reflects the particles moving in the crushing stream. The working chamber with a fluidized layer is cylindrical. The crushing nozzles are located at the same height, closer to the bottom of the chamber, so that the crushing streams compensate each other, eliminating the wear of the chamber walls and creating a fluidized layer.

The mathematical model was calculated using the Quattro Pro database.

3. Results and analysis

The mathematical model for optimizing the glass crushing process in a jet mill. A theoretically accurate description of the glass crushing process requires consideration of a wide range of factors. First of all, this is energy for ultimate elastic and plastic irreversible deformations which determine the nature of the model. There are other energy costs - for friction and formation of aggregates, etc. Due to the low level of knowledge of the latter, without losing the qualitative adequacy of the model, we can analyze ultimate elastic deformations.

With a certain degree of approximation, we can assume that

\[ D_w = K_d (1 - S / S_m) \]  

where \( W \) - particle energy density, \( S \) – specific surface of the particle, \( S_m \) - specific surface of finely ground powder, \( \varepsilon \) – crusher’s energy, \( K \) – crusher’s efficiency. When crushing, the specific surface of particles \( \xi \) approaches the value of the specific surface \( S_m \) of the crushed powder, with a certain given particle size

Let us integrate the equation.

\[ S = S_m (1 - e^{-K_2 t}) \]  

where \( -K_2 = K_1 N / V \) – crusher’s power, \( V \) - volume of crushed powder, \( K \) - efficiency of the impact destruction of a particle equal to the ratio of destruction energy to the total value of the kinetic energy of a particle before the impact.

The most important characteristics of this model is the exponential nature of the asymptotic approximation to the conditioned value \( S_m \).

\( V \) is not constant during the process. It follows from (2) that a decrease in \( V \) accelerates the convergence of \( S \) up to \( S_m \).
The qualitative model determines the approach to the regression based on the experimental data presented below for 0.1 < S < 0.2.

The regression equation of the crushing process can be written as

\[ Y = 1 - at^2 e^{-bt} \]  

(3)

y is the estimate of the output parameter (the percentage of output of the required fraction); the exponential component reflects the qualitative behavior of the model, and its quadratic term reflects its specificity; \( t \) is the input parameter (time).

Using the logarithm for (3), we have

\[ \ln(1-y) = \ln a + 2 \ln t - b \cdot t. \]  

(4)

For the regression, let us use the least squares method, determining constants \( a, b \), from the following system of normal equations:

\[
\begin{align*}
\Sigma \ln_i &= n \ln a + 2 \Sigma \ln t_i + b(\Sigma t_i) \\
\Sigma t_i \ln x_i &= (\Sigma t_i) \ln a + 2 \Sigma (t_i n t_i) + b(\Sigma t_i ^2) \\
\Sigma (t_i \ln x_i) &= (\Sigma \ln t_i) \ln a + 2 \Sigma \ln x_i ^2 + b(\Sigma t_i \ln t_i)
\end{align*}
\]

where \( n=3 \), the number of tests. Substituting values of \( y \) and \( t \), we can solve the system of equations: \( a=16.3173, b = 3, 8739. \)

Inadequate models of the curve’s behavior at the time duration more than 0.5 hours are due to the fact that the energy consumption for plastic deformations becomes predominant when most particles are small. The mathematical model of the dependence of the glass yield with a particle size of -0.2 + 0.1 on the crushing time satisfies the conditions. At 0.5 hours, the function monotonically increases.

4. Discussion

The optimal particle sizes used as a binder for producing the mica composition are -0.2 + 0.1.

The crushing efficiency for various materials can be estimated by a universal criterion - the energy consumption for the formation of a specific surface unit. The ratio between the growth of the specific surface and the energy consumption depends on the properties of the material, the crushing method, the crushing machine, and the crushing time. An increase in the energy consumption always outstrips an increase in the specific surface. Ball crushing is not suitable for fine glass crushing. Glass crushed in ball mills contains a significant amount of the over-crushed material. The difficulty in using ball or rod mills is due to the fact that the hardness of available structural steel for the production of crushing bodies is equal to the hardness of glass. In addition, this material has abrasive properties. Thus, glass should not be crushed in such mills.

Self-crushing mills are widely used. They improve productivity and decrease energy costs.

In many industries, where particles of less than 10 microns are needed, jet mills are used. The domestic industry uses plants for crushing granite, coal, coke, limestone, quartz and other minerals to a particle size of 60-70 microns. As an energy carrier, superheated steam, compressed air, and gas-vapor mixture are used. Jet crushing plants are based on the self-crushing principle during the collision of particles in the crushing chamber, moving bodies in energy flows towards each other. The plant consists of a feeder, a divider, and injection chambers with booster tubes. The crushed material is separated in the divider, from which the material of a required dispersion is sucked into the dust collection system, and larger particles are recrushed. The vacuum is created by a centrifugal fan.

The counter-current jet mill is of great interest. When crushing glass in the jet mill, the main task is to establish the relationship between the dispersion of the crushed material and energy costs of the mill with given design parameters. The crushing kinetics is determined by the significant and simultaneous influence of many factors: plastic and elastic deformations, interaction of particles between themselves and the environment, large-scale changes in strength, and design features of the crusher. These features determine the complexity of the crushing problem which has not been solved yet.
The ratios of Rittinger, Kick, and Bond are based on the one-sided consideration of any parameters. Therefore, there are rarely used to describe the experimental data. It is necessary to consider the theory of glass crushing using the mathematical model, take into account the time-related energy consumption for ultimate elastic and plastic deformations of glass in order to produce the material of this class of fineness.

5. Conclusion
The research results showed that the mathematical model designed to optimize the glass crushing process in the jet mill can increase the glass yield, help produce particles of a required size with minimum energy costs. Energy costs for plastic deformations become predominant when particles are small. The maximum yield of particles -0.2 + 0.1 in size (89.9%) was achieved for the minimum crushing time (1.5 hours). The specific surface of particles is equal to the specific surface of extremely finely crushed glass powder.

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