KINETICS OF DOLOMITE GRINDING IN A LABORATORY BALL MILL

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ABSTRACT:
Grinding is one of the most widely used methods of obtaining solid particles of controled/ desired distribution systems in all branches of industry. Enlargement of this process is often based on experience and on trial and error methods that requires a large number of experiments. The development of mathematical models enabled the transfer of results to a larger scale in similar systems. The proposed researches were conducted in a laboratory scale. The modeling of the grinding process by the population balance included a description of the kinetics of dolomite grinding by kinetic parameters and the development of models that enabled the estimation of kinetic parameters on the basis of the particle size, the geometric characteristics of the mill and the process parameters. Rajamani and Herbst model is suggested for the development of selection function in a ball mill under given conditions process. The selection function was determined based on the change in the proportion of unbroken material over time for eight size intervals in four mills of different volumes, using one-size interval method. Change of unbroken material content with time is linear.The specified dependence suggests first-order breakage kinetics. The selection function was then described by the Rajamani Herbst model. Laboratory-level researches and the development of mathematical models for transferring results to a larger scale is a potential way of reducing energy consumption.

KEYWORDS: ball milling, kinetic, grinding, mathematical model

INTRODUCTION

Grinding is the process of reducing the size of a raw material for its direct use or mineral raw material for the concentration process, or other form of technological processing. As the size decreases, the surface area of the raw material increases. Therefore, it can be said that grinding is a process that leads to the creation of new surfaces.[1]

Apart from its technological importance which is reflected in the reduction of its size and the release of minerals, grinding also has important economic importance. About 4.5-5% of produced electricity in the world is spent on the grinding of various materials. Grinding is a very expensive process. Considering the energy consumption and the equipment cost, improvements in the grinding process are of great economic and therefore environmental importance.

The most well-known method of controlled production of these sizes is grinding in ball mills. This process is the subject of much research today if considered high energy consumption in the grinding process and its versatile application in industry.[2,3] One of the research directions is focused on studying the legality of the grinding process and, on the basis of them, defining mathematical models of grinding that represent the basis for optimization and automation of the grinding process.[4,5]

Optimal design and control of the grinding process requires a good selection of a mathematical model that will allow the prediction of material behavior in the grinding process The most commonly used tool to simulate the grinding process are population balances that describe the change in mass of particles of a given size in a given time. In conditions of discontinuous grinding , the population balance means a description of the process by the basic functions: by a selection function that defines the probability of fracture of a given size material, and by a fracture function that defines the distribution of fracture products.[6,7]

The selection function and the fracture function can be determined experimentally on a small scale and used for the product properties prediction on an industrial scale.

These functions depend on the process conditions and the particle size distribution of the input current of the material. They are experimentally determined on a small scale. However, their direct determination in large volume mills is almost impossible. Therefore, it is necessary to extrapolate the results obtained on a smaller scale. The particle size distribution of the grinding products depends on a number of factors: characteristics of the input material, mill speed, type, size and number of grinding bodies, distribution of grinding body sizes. Process parameters affect kinetic parameters: selection function and fracture product distribution function.[8]

Rajamani Herbst model

$$\ln\left(\frac{S_j}{S_1}\right) = \alpha_1 \cdot \ln\left(\frac{x_j}{x_1}\right) + \beta_1 \cdot \left[\ln\left(\frac{x_j}{x_1}\right)\right]^2 \quad (1)$$

For a wide range of size intervals, Rajamani and Herbst used a polynomial function to estimate the selection function.[9,10]. This model actually represents a second-degree polynomial with coefficients, where parameter α1 denotes particle size for maximum selection function (turning point), and parameter β1 denotes sharpness of turning point for larger particles. Using the experimental data, the specified parameters are determined. If there is a significant deviation from the literary model proposed to describe the selection function from the experimental data, a model to adequately describe the change in the selection function with particle size must be sought.

When choosing a mathematical model, the model with shorter duration of the experiment is chosen.

Austin model

$$S_j = S_1 \cdot \left(\frac{x_j}{x_1}\right)^a \quad (2)$$

If the diameter of the ball mill is appropriately selected and the particle size input is less than 1mm, the second part of the Rajamani and Herbst model can be neglected, and the function becomes the Austin model.[8]

In the expression xj, upper limit of interval marked as the j-interval, and α is a model parameter that depends on the material properties and the grinding conditions.

Snow model

$$\frac{S_j}{S_{max}} = \left(\frac{x_j}{x_{max}}\right)^c exp\left(-\frac{x_j}{x_{max}}\right) \quad (3)$$

Snow introduced a mathematical model that describes the change in selection function with maximum selection function and particle size.[11,12] This model is often used with certain corrections, that is, it is not applied without additional corrections.

MATERIALS AND METHODS

Tested system

Experimental researches were conducted on a model dolomite sample Samoborka d.o.o.Zagreb. Dolomite is a part of sedimentary carbonate rocks of about 10%, consisting mainly of dolomite minerals. Theoretically, dolomite contains 54.35% $CaCO_3$ and 45.65% $MgCO_3$ impurities such as Si-, Al- and Fe and oxides. For commercial purposes, the proportion of these impurities should not exceed 7%, since then its industrial use becomes questionable. The sample was divided into eight one-particle intervals defined by the mesh diameter of the sieve.

Table 1. One-particle intervals

Size interval	Size range, μm
M1	1700 – 1180
M2	1180 – 850
M3	850 – 600
M4	600 – 425
M5	425 – 300
M6	300 – 212
M7	212 – 150
M8	150 – 106

The particle size intervals are chosen in a way that the ratio of the upper and lower interval sizes is always √2 as defined by the ASTM sieve standard.

Grinding machines (ball mills)

The grinding of the material in the ball mill occurs primarily due to the kinetic energy consumption of the normal ball impact. The most effective action of the balls in the mill is achieved at the speed of rotation of the mill, for which the total kinetic energy of the normal impact of the ball in the unit of time is maximum. Starting from these assumptions, theoretical expressions were obtained for the optimum rotation speed of ball mills in terms of the kinetic energy of the balls. The optimum speed is reached at 60 to 80% of the critical speed. Various shapes (balls, bars, prisms, cubes, etc.) can be used as grinding balls.[13] The best results with regard to the efficiency of grinding were given by rods and balls. Apart from the wear resistance, an important feature of the bars and balls is their even wear, i.e. retaining their original shape.

The filling of the mill with the grinding balls is characterized by afilling coefficient (φ). The grinding balls rotate together with the pot. Centrifugal force and gravitational force affect the ball (grinding balls) in the mill:

$F_c = m \cdot \omega^2$ .... (4)
$F_g = m \cdot g$ .... (5)

F_p- centrifugal force (N)
F_g-gravitational force (N)
g-gravitational acceleration (m/s^2)
ω-angular velocity (^{o}/s)
m-mass (kg)

At the moment of equalization of centrifugal force and force of gravity, material centrifugation occurs, and the speed at which this occurs is called the critical speed.[14]

$$n_{kr.} = \frac{42{,}3}{d_u^{0,5}} \quad (6)$$

n_{kr}- critical speed of the ball mill (^{o}/s)
d_u- the inner diameter of the ball mill vessel (m)

Figure 1. Ball mill

ANALYSIS BY SIEVES

The particles size distribution samples grinded over a shorter period of time was determined by analysis by sieves For this purpose, sieves whose mesh aperture is shown in the table and defined by the ASTM standard were used. In this way, the proportion of particles in a given particle size interval is obtained. For comparison with the computationally obtained distribution of particle sizes, the experimental values were translated into cumulative form.[15]

DETERMINING THE SELECTION FUNCTION (S-FUNCTION)

The selection function, Si, is also called the specific fracture rate. It is the mass fraction of size particles that is selected and broken in a unit of time.[16,17] Represents the probability that a particle of size xi is selected for breaking and broken to a size smaller than the lower limit of the interval i (x_{i+1}).

The most common methods for determining the selection function are, - a one-size intervals method in which the loss of material from the initial *j* interval is monitored[18] - a radioactive labeling method in which the particle's path is traced through size classes during the grinding process. It is determined by the one-size intervals method.[15] The sample is divided into narrow particles size intervals. According to the ASTM sieve standardization, the ratio of the upper and lower bounds of the interval is $\sqrt{2}$ or $\sqrt[4]{2}$. Each interval is grinded separately and the proportion of unbroken interval material *j* in time is monitored. Assuming that the fracture kinetics of individual particle sizes is a first order process, the velocity of disappearance of that size is proportional to the mass of the same. With the application of the one-size interval method, the function of formation is lost. The rate of disappearance of particles from the initial interval can be described by the expression. [5,13,18,19]

$$\frac{dw_i(t)}{dt} = -S_1 \cdot w_1(t) \quad (7)$$

Where S1 is the constant of proportionality and is called the specific fracture rate. With the integration of the expression in the range from 0 to t, the following equation is obtained:

$$w_1(t) = w_1(0) \cdot \exp\,(-S_1 \cdot t) \quad (8)$$

Which logarithmically transforms into a form that forms the basis for determining the specific fracture rate of a given size.

$$ln\, w_1(t) = ln\, w_1(0) - S_1 \cdot t \quad (9)$$

Since, according to the one-size interval method, all particles are located in initial interval *i*, $w_i(0)=1$, equation (9) goes to the simplest form of equation of the direction whose direction coefficient represents the value of the specific fracture velocity:

$$ln\, w_1(t) = -S_1 \cdot t \quad (10)$$

If the specific fracture rate is constant, the fracture kinetics is of the first order, which means that the accumulation of particles in the pot has no particular influence on the specific fracture rate. Based on the above expression,by the method of one-size intervals, the values of the selection function (specific fracture velocity) of all 8 particle size intervals (i = 1 ... 8) were determined.

RESULTS AND DISCUSSION

Based on the one-size intervals method, the values of the selection function are determined, assuming that there is no their change in time, that is, it is a first order process. The selection function is determined by the change in the proportion of unbroken material in time. (Fig.2) shows the experimental results on the basis of which the selection function was determined for the mill 400 ml and for the size interval 1700-1180µm. In this way, we determined the selection function for all size intervals in all four mill volumes.

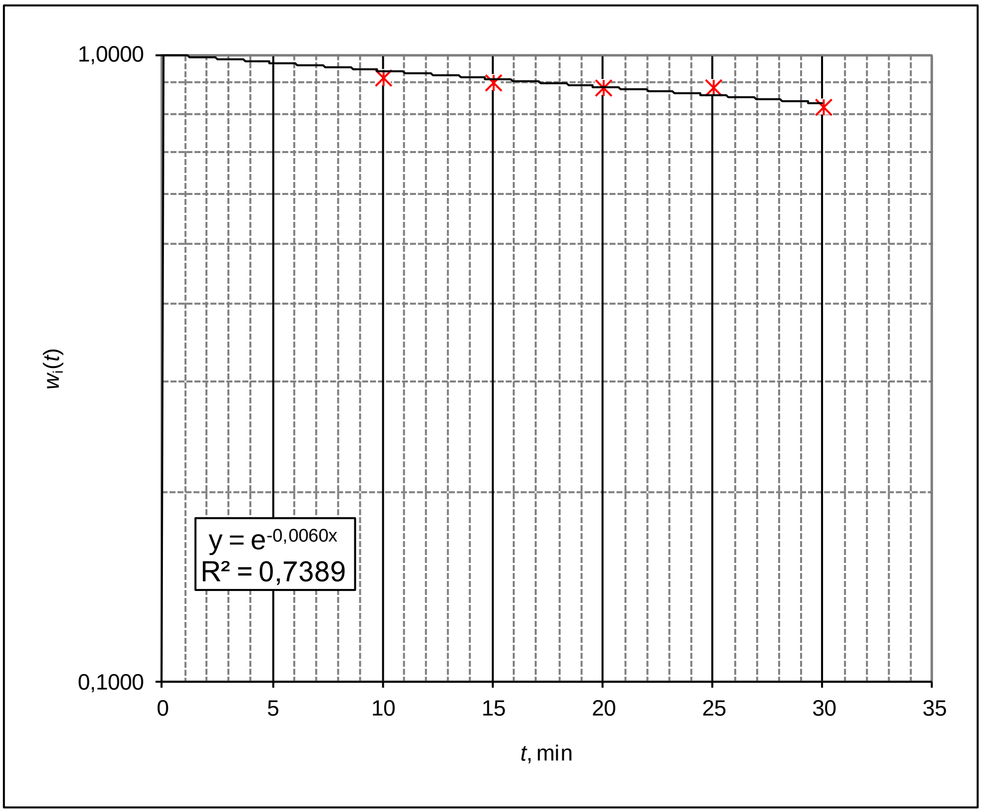

Figure 2. Change in the proportion of unbroken material in time; mill 400ml, 1700-1180 µm

Table 2. The view of all obtained values of the selection function.

S_j, s^{-1}		x_i, µm							
		1180	850	600	425	300	212	150	106
V, m^3	0,0004	1,00E-04	2,22E-04	4,72E-04	5,98E-04	6,67E-04	1,17E-03	8,80E-04	4,85E-04
	0,001	1,77E-04	2,48E-04	3,75E-04	5,48E-04	5,53E-04	8,40E-04	7,42E-04	3,77E-04
	0,0017	2,12E-04	2,58E-04	3,12E-04	3,90E-04	3,83E-04	6,48E-04	4,57E-04	2,43E-04
	0,002	2,25E-04	2,63E-04	3,27E-04	3,57E-04	3,38E-04	5,72E-04	3,78E-04	2,10E-04

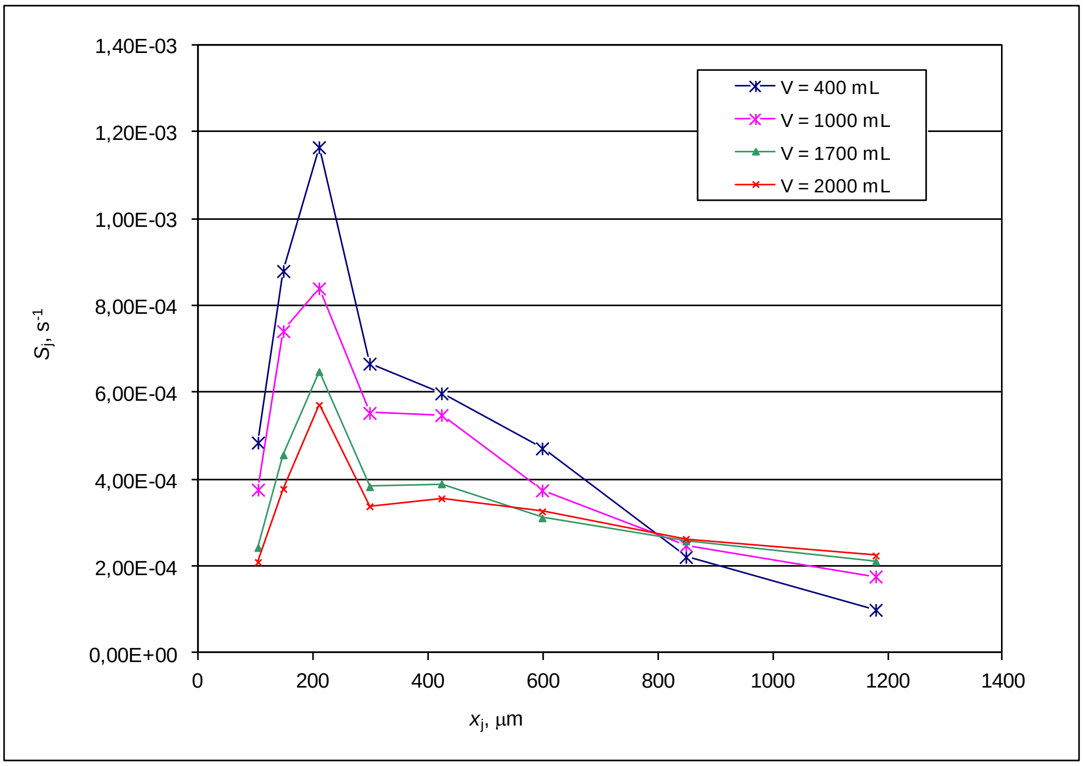

Figure 3. Dependence of the selection function on the particle size.

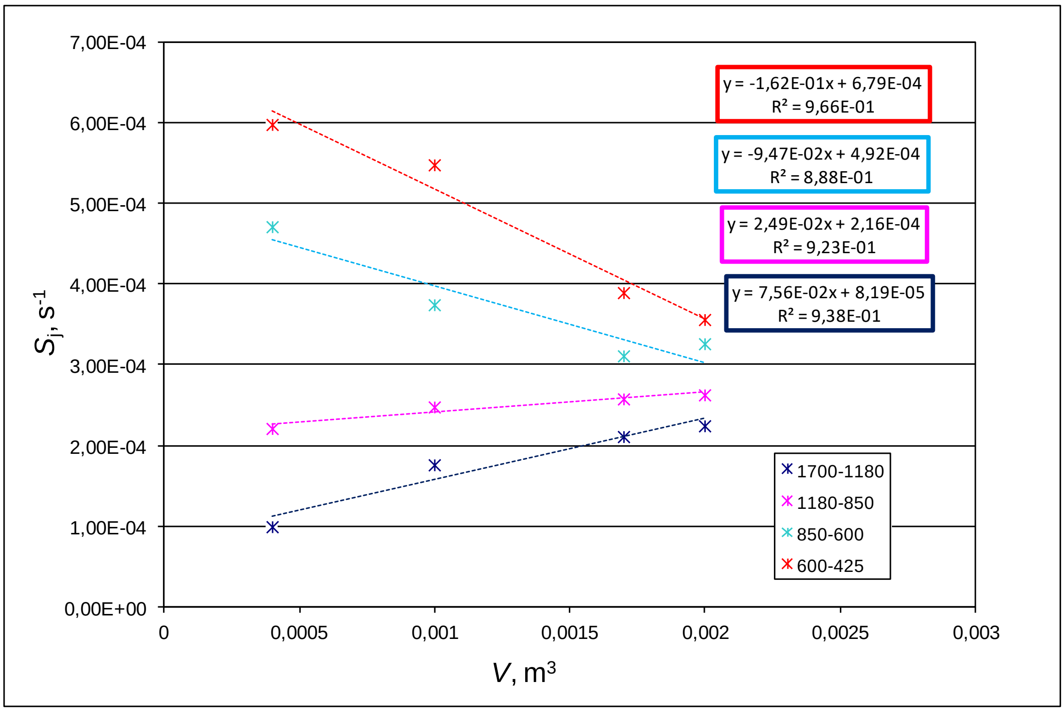

Figure 4. Dependence of the experimentally obtained values of the selection function on the volume of the mill drum; intervals M1, M2, M3 and M4.

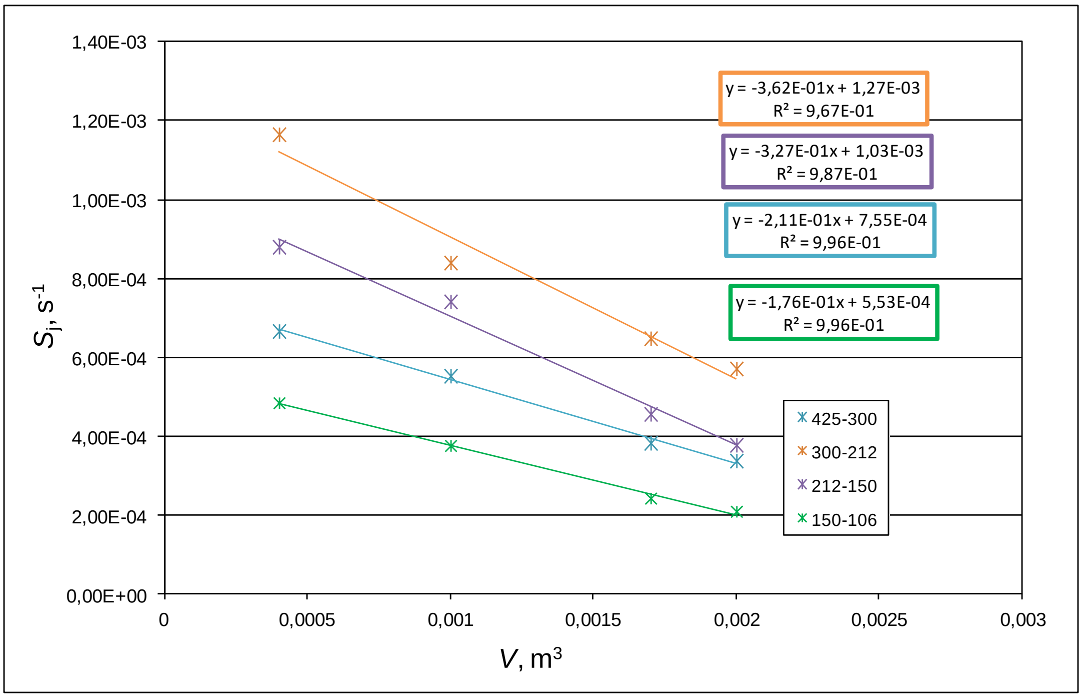

Figure 5. Dependence of the experimentally obtained values of the selection function on the volume of the mill drum; intervals M5, M6, M7 i M8

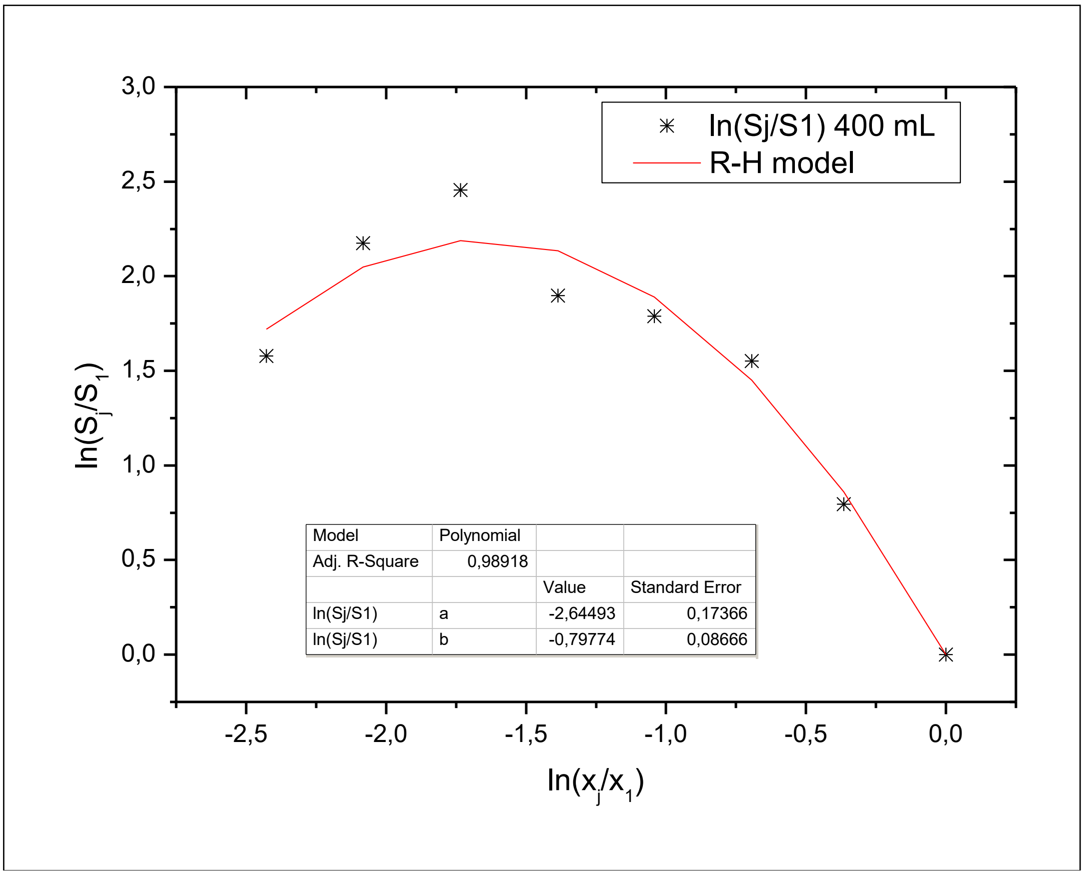

Figure 6. Describing the specific fracture velocity by the Rajamani-Herbst model, mill volume 400 mL.

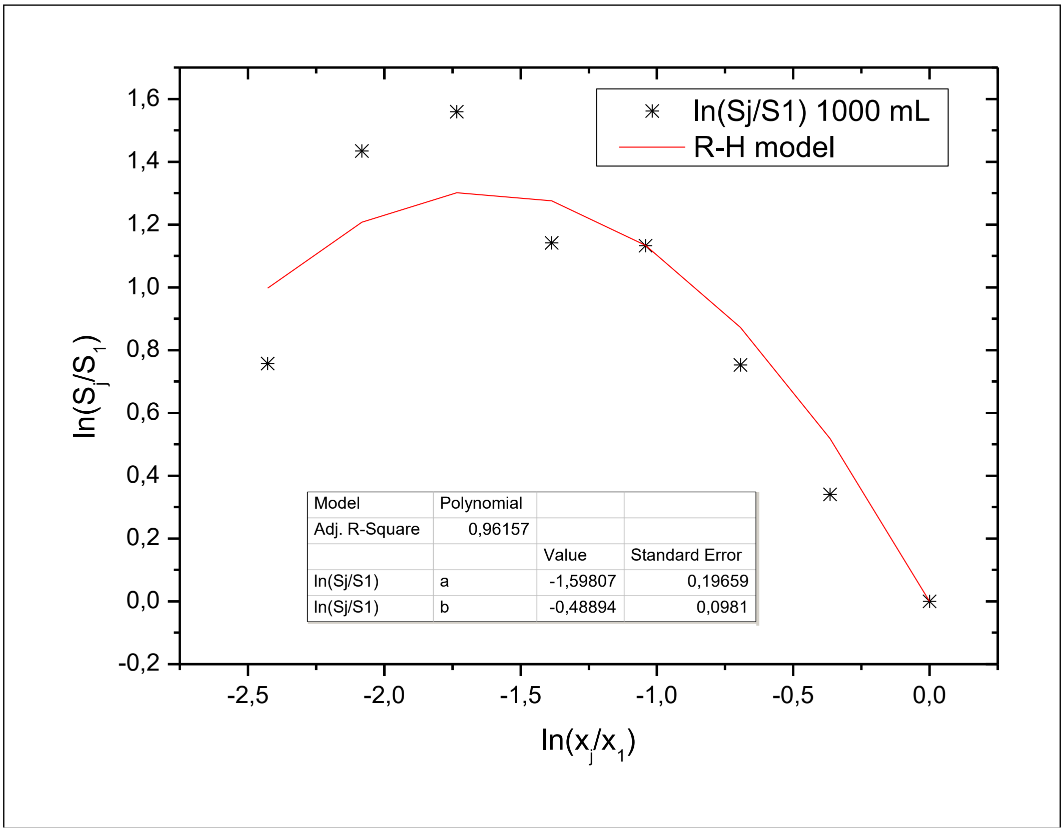

Figure 7. Describing the specific fracture velocity by the Rajamani-Herbst model, mill volume 1000 mL.

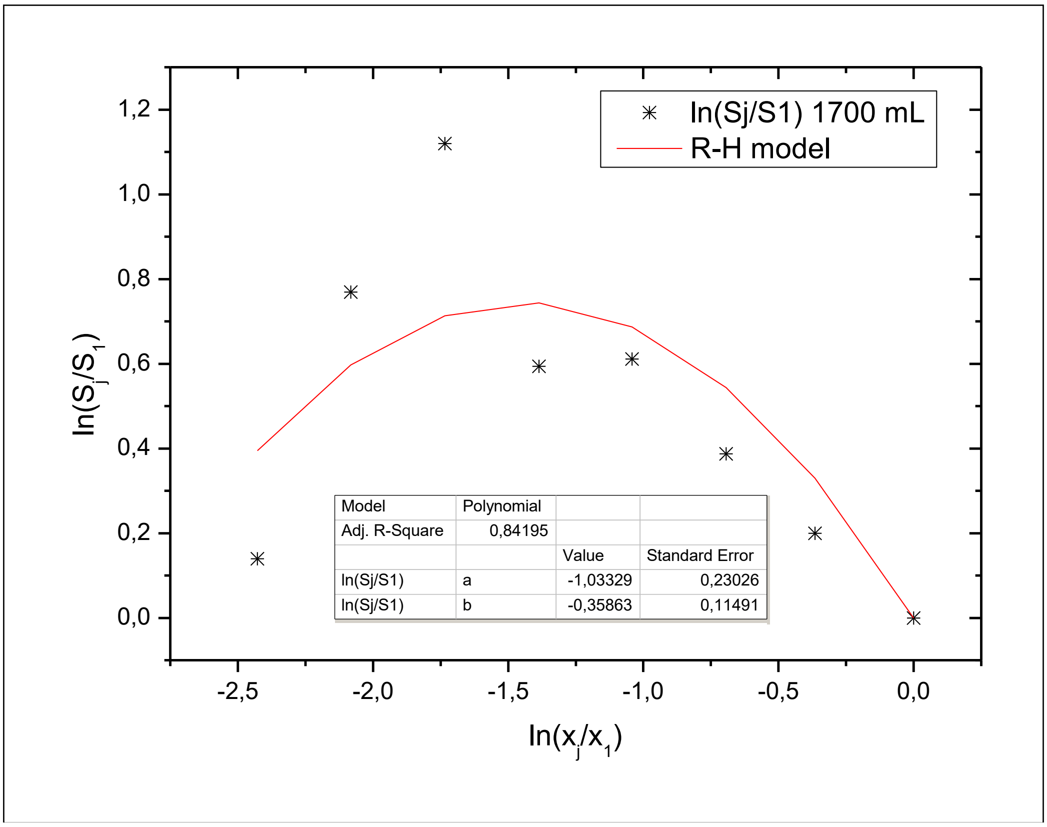

Figure 8. Describing the specific fracture velocity by the Rajamani-Herbst model, mill volume 1700 mL.

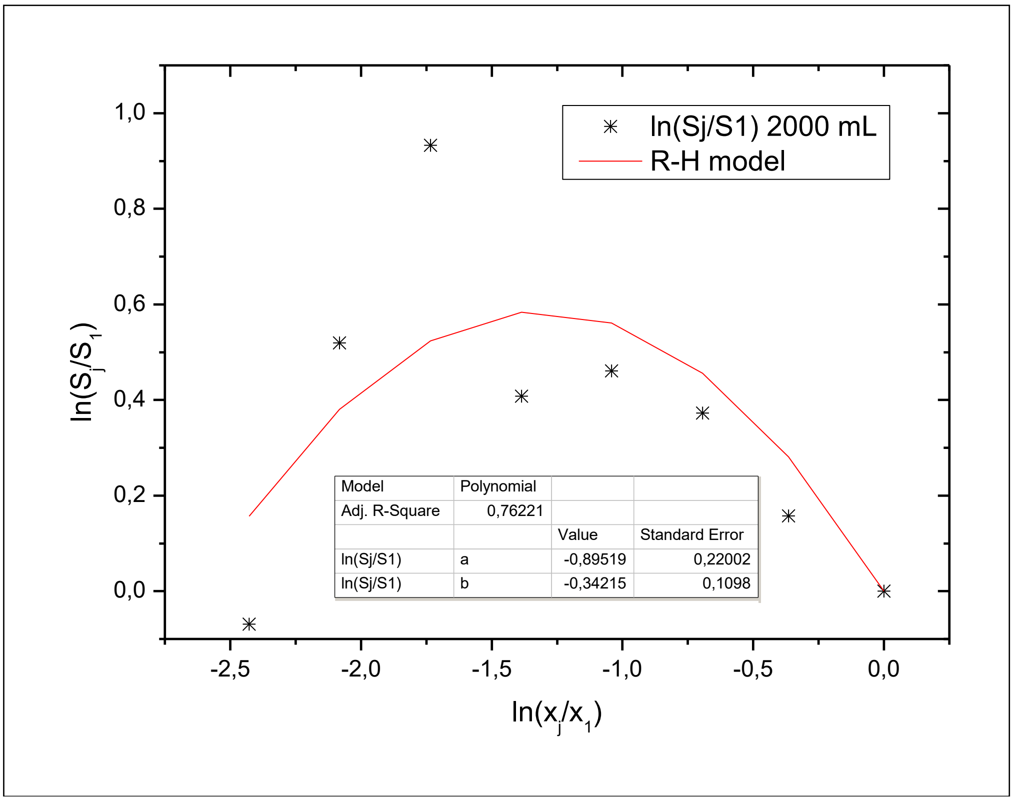

Figure 9. Describing the specific fracture velocity by the Rajamani-Herbst model, mill volume 2000 mL.

For many researchers, the focus of the work is on development and application of suitable grinding models, due to both widespread use and high energy intensity. By knowing the selection function and the distribution function of the breakage products, it is possible to predict the property of the resulting product and transfer the results to a larger scale. The samples were divided into eight particle size intervals. The study of grinding kinetics was carried out in mills of different volumes (400, 1000, 1700, 2000 ml).

Based on the results, it can be seen that the proportion of unbroken material in the initial interval changes linearly with time. (Fig.2) Which means that the kinetics of dolomite grinding in a ball mill takes places according first- order breakage kinetics. Bigger ball mills are more efficient for coarse particles because coarser particles need the higher fracture energy possessed by the larger balls. Smaller ball mills have a larger surface and are more efficient for particles smaller than 0.212 mm. (Fig. 4,5) Namely, by increasing the diameter of the grindng balls, more efficient grinding of larger particles is achieved, since larger balls result in collisions of higher specific energies. [11]

With grinding, the proportion of cracks in particles is reduced and the grinding process slows down. The particles tend to break because they are smaller and more regular. Therefore, it is advisable to use more energy, because, in that way, the particles of a more regular shape will be broken as well. The values of R^2 show a deviation from the experimental and by the model obtained values. It was shown that at the 400 and 1000 mL mills, the R-H model describes the experimental data well. (Fig. 6, 7). However, by increasing the scale, a significant deviation occurs and a correlation coefficient of 0.7622 is by no means acceptable since it is considered that further magnification would lead to even greater deviations and inability to predict selection function. (Fig. 8, 9) Since, at all volumes, the maximum values of the selection function are obtained at the same particle size (212 m), it is expected to achieve this maximum with further magnification. We tried to use the Snow model which requires knowledge of the maximum value of the selection function and the size at which this is achieved. However, the results showed even greater deviations and the Snow model cannot be used. With the appropriate model, the coefficients of the model can be correlated with mill volume or other sizes (diameter, diameter of the grinding body, power).

The values of the model parameters depend on the type of raw material and the grinding conditions, which makes this process complex. Therefore, no correlation has yet been established between model parameters in laboratory and industrial mills.

CONCLUSIONS

Following the process of dry grinding of dolomite in a ball mill, the linear dependence of the change in the mass share of the unbroken material over time was determined which indicates that dolomite grinding kinetics is a first order process.

The applicability of the Rajamani and Herbst models was investigated. The Rajamani and Herbst model can be used for estimation of the selection function under given process conditions. Model parameters can be correlated with mill diameter, balls diameter. According to the results obtained, it can be concluded that it is possible to estimate the model parameters and the selection function following the proposed methodology. The disadvantage of this model is that it is limited to mill diameter up to 30 mm. The inability to predict the change in model parameters with the change in the characteristics of the material which is grinded and the conditions of grinding greatly diminishes its practical value. Despite the great effort put into improving the grinding process, its inefficiency is still significant, and the process design and magnification are based more on experiential rules than theoretical and empirical models.

REFERENCES

[1] V. Deniz, The effect of mill speed on kinetic breakage parameters of clincer and limestone, Cement Concrete Res., 34 (2004) 1305 – 1377

[2] S. Fadda, A. Concas, A. Cincotti, M. Pisu, G. Cao, Modelling breakage and reagglomeration during fine dry grindig in ball milling devices, Powder Technol. 194 (2009) 207-216

[3] H. Benzer, Modeling and simulation of a fully air swept ball mill in a raw material grinding circuit, Powder Technol.150 (2005) 145 – 154

[4] Y. T. Man, Model-based procedure for scale-up of wet, overflow ball mills part III: validation and discussion, Miner. Eng. 14 (10) (2001) 1259-1265

[5] D. W. Fuerstenau, A. De, P. C. Kapur, Linear and nonlinear particle breakage processes in Comminution systems, Int. J. Miner. Process. 74S (2004) S317 – S327

[6] V. Deniz, T. Onur, Investigation oft he breakage kinetics of pumice samples as dependent on powder filling in a ball mill, Int. J. Miner. Process. 67(2002) 71-78

[7] G. Matijašić, A. Glasnović, Batch grinding in laboratory ball mills: selection function, Chem. Eng. Tech. 32 (10) (2009) 1-8

[8] Y. Umucu,V. Deniz, The evaluation of grinding behaviors of quartz and feldspar, TOJSAT(2014)

[9] R. K. Rajamani, J. A. Herbst, Simultaneous estimation of selection and breakagefunctions from batch and continuous grinding data, Trans. Inst. Miner. Metall. Sec. C93 (1984) C74–C85

[10] C. Hosten, An alternative solution to the grinding equation in cumulative size distribution form, Miner. Eng. 18 (2005) 489–493

[11] R. H. Snow, Grinding ball simulation and scale-up of ball mills, in: D. Wanson (Ed.), Advances in Particle Science and Technology, Academic Press, 1973.

[12] N. Kotake, K. Suzuki, S. Asahi, Y. Kanda, Experimental study on the grinding rate constant of solid materials in a ball mill, Powder Technol. 122 (2002) 101–108

[13] L. G. Austin, A discussion of equations for the analysis of batch grinding data, Powder Technol. 106 (1999) 71-77

[14] M. Hraste, Mechanical Process Engineering. Hinus, Zagreb, 2003.

[15] G. Matijašić, Rheological behavior and granulometric properties of dense suspensions in the grinding process FKIT Zagreb, (2006)

[16] H. Ipek, Y. Ucbas, M. Yekeler, C. Hoşten, Dry grinding kinetics of binary mixtures of ceramic raw materials by Bond milling, Ceramics Int. 31 (2005) 1065-1071

[17] Y. Wang, E. Forssberg, Enhancement of energy efficiencyfor mechanical production of fine and ultra-fine particles in comminution, China Particuology 5 (2007) 193-201

[18] L. G.Austin, V. K. Bhatia, Experimental methods for grinding studies in laboratory mills, Powder Technol. 5 (1971/72) 261-266.

[19] E. Teke, M. Yekeler, U. Ulusoy, M. Canbazoglu, Kinetics of dry grinding of industrial minerals:calcite and barite, Int. J. Miner. Process. 67 (2002) 29 – 42

[20] A. S. Erdem, S. L. Ergun, The effect of ball size on breakage rate parameter in a pilot scale ball mill, Int. J. Miner. Process. 29 (2009) 660 – 666

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