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AN OPTIMIZATION OF CALCITE GRINDING USING THE TAGUCHI METHOD WITH MULTIPLE PERFORMANCE CHARACTERISTICS

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Abstract

The purpose of this study is to demostrate how the application of Taguchi method can be used to develop an effective optimization process for calcite grinding. In order to observe the influencing degree of contol factors in dry calcite grinding, three control factors namely mill speed, ball size and grinding time on lowest product 80% passing size (d_{80}) were studied and optimized. L_{18} orthogonal array, by which the effect of one factor has six levels and others have three levels, could be tested, was chosen. The optimal process control factors which minimize the d_{80} size of product were the mill speed (%Critical) at %70, ball size at 20 mm and the grinding time at 30 min with the prediction of 49 mm d_{80} size. The mill speed has stronger effect on the calcite grinding process followed by the grinding time and the ball size. In order to gain a better understanding of the effects of control factors on d_{80} size, a total of 3 response surface plots for the measured response were formed. The study indicated that the Taguchi method was an efficient way of determining the optimal grinding parameters for calcite grinding.

Keywords: Taguchi method; calcite grinding; optimization

1. Introduction

At present, the demand for fine particles has continuously increased. The manufacturing industry is setting a very stringent specification for these particles including finer particles with closer control of mean particle size or width and cut-off of the particle size distribution [1-3].

On the other hand, grinding is a highly energy consuming process. According to statistics, in mineral processing, comminution accounts for a substantial portion of the energy consumed in the plant, almost 80% [4]. Therefore, a small gain in comminution efficiency can have not only a large impact on the operating cost of a plant, but also a reduction in greenhouse gas emission [5]. In recent years, thus, significant steps have been taken to improve comminution efficiency both in the development of machines with the ability to enhance energy utilization and in the optimal design of grinding systems to enable more efficient use of existing machines [6-7]. In this context, a large number of experimental investigations concerning to grinding optimizations have been carried out by researchers over the past few decades. But it is still necessary to have a better knowledge of the effects of mill operating parameters if optimal performance is to be achieved. Many parameters can affect the efficiency and productivity of a dry grinding system, such as operational speed, fractional ball filling, feed rate, material hardness and feed size. Optimizing these parameters in the grinding systems is an important step in minimizing the cost of production [5-6].

Taguchi method is an efficient problem-solving tool, which can upgrade/improve the performance of the product, process, design, and system with a significant reduce in experimental time and cost [8]. This method combining the experimental design theory and quality loss function concept has been applied for carrying out robust design of processes and products and solving several complex problems in manufacturing industry [9]. Further, this technique determines the most influential parameter on the output response for the significant improvement in the overall performance. The purpose of this study is to demostrate how the application of Taguchi method can be used to develop an effective optimization process for calcite grinding. An optimization of calcite grinding based on a ball bill using the Taguchi method with multiple performance characteristics is proposed.

2. Experimental material and grinding tests

Dry grinding experiments on calcite were carried out using a laboratory batch ball mill. The stainless steel mill had inner dimensions of 209 mm and 175 mm length with six lifters bars (20 mm in diameter). Critical rotation speed (N_C) is 102 rpm for the ball mill. For all experiments, the calcite sample obtained from Sivas-Kangal region (Turkey) was prepared using a √2 sieve series to be used as the feed charge. The calcite feed weight was held constant at 400 g, which was -1000 μm and had 760 μm of the d_{80} size. The fractional ball charge was 0.20 for each test. After each grinding test, the balls were cleaned and removed from the mill one by one, and the product was sampled for size analysis and the d_{80} was determined. The particle size analysis of the products was determined by dry sieving technique.

3. Experimental design

The experiments were carried out to analyze the influence of control factors on calcite grinding process, the code and levels of three control factors namely the mill speed (% Critical), the ball size and the grinding time are shown in Table 1. L_{18} orthogonal array, by which the effect of one factor has six levels and others have three levels, could be tested, was chosen. A standard Taguchi orthogonal array with notation $L_{18}(6^{**1}3^{**2})$ was chosen. Maintaining these control factors, the other operating conditions were kept constant at those mentioned above.

Table1. Process control factors and their levels

Control factors	Symbol	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
Mill speed (%Critical)	*A*	%60	%65	%70	%75	%80	%85
Ball size (mm)	*B*	20	30	40	-	-	-
Grinding time (min)	*C*	10	20	30	-	-	-

After the experiments are conducted, the optimal control factors configuration within the experiment design must be determined. To analyze the results, the Taguchi method uses a statistical measure of performance called signal-to-noise (S/N) ratio. The S/N ratio, the ratio of the mean (signal) to the standard deviation (noise), is a performance measure to choose control levels that best cope with noise. The S/N equation depends on the criterion for the quality characteristic to be optimized. While there are many different possible S/N ratios, three of them are considered standard and are generally applicable in the most situations: the-bigger-the-better, the-smaller-the-better and the-nominal-the-better. Whatever the type of quality or cost characteristic, the transformations are such that the S/N ratio is always interpreted in the same way: the larger the S/N ratio the better. In this study, the-smaller-the-better quality characteristic was taken due to investigating the influence of control factors on calcite grinding process. The S/N ratio for each level of control factors was computed based on the S/N analysis.

4. Results and discussion

4.1. Analysis of control factor

For dry calcite grinding process, analysis of the influence of each control factor on the d_{80} size has been performed with a so-called signal-to-noise (S/N) response table. Table 2 shows the experimental layout and results of calcite grinding process. It shows the S/N ratio at each level of control factors and how it is changed when settings of each control factor are changed. The influence of interactions between control factors is neglected here. Fig.1. shows the main effect graphs for S/N ratio. The control factor with the strongest influence is determined by differences values. The higher the difference, the more influential is the control factor. Optimal grinding conditions of these control factors can be very easily determined from the S/N response graphs in Fig.1 for this process. The S/N ratio can also be calculated in the following form [10-12]:

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^{\,2}\right) \tag{1}$$

where S/N is performance characteristics, n the number of repetition done for an experimental combination (in this study n = 1), and y_i the performance value of ith experiment. Notice that S/N ratio is expressed in a decibel scale.The best d_{80} value is at the higher S/N values in the response graphs. Optimal grinding conditions of ball mill for calcite grinding are shown in Table 3. The rank (1) in this table indicates that the mill speed has stronger effect on the process followed by the grinding time and the ball size on the process. Response surface analysis (Figs.2-4) also indicates the minimum d_{80} size at level 3 of mill speed (%Critical) and grinding time with at level 1 of ball size.

Table 2. Experimental layout and results of grinding process

	Levels of control factors				
Run	*A*	*B*	*C*	d_{80} (μm)	S/N ratios (dB)
1	1	1	1	96	-39,69
2	1	2	2	101	-39,96
3	1	3	3	92	-39,35
4	2	1	1	86	-39,07
5	2	2	2	93	-39,34
6	2	3	3	90	-38,73
7	3	1	2	61	-34,98
8	3	2	3	59	-35,73
9	3	3	1	84	-38,90
10	4	1	3	53	-35,33
11	4	2	1	107	-39,87
12	4	3	2	88	-38,77
13	5	1	2	60	-36,01
14	5	2	3	68	-36,77
15	5	3	1	106	-39,94
16	6	1	3	65	-35,27
17	6	2	1	93	-39,81
18	6	3	2	81	-38,72

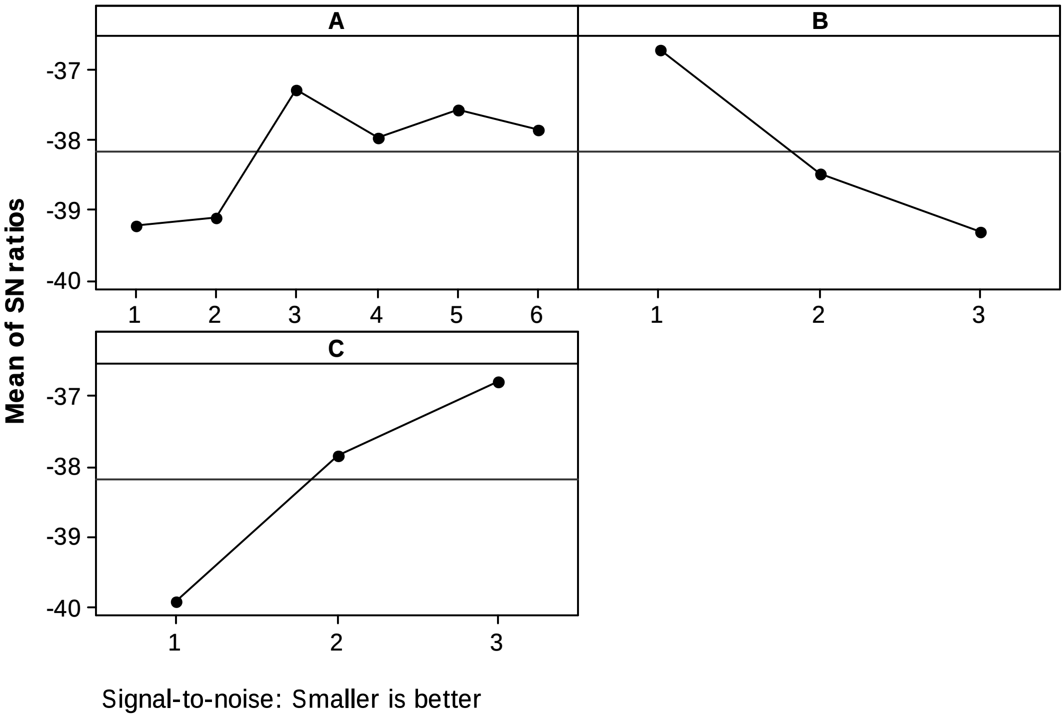

Fig.1. Main effect graphs for S/N ratio

4.2. Three-dimensional response surface plots

In order to gain a better understanding of the effects of control factors on d_{80} size, a total of 3 response surface plots for the measured response were formed. Also the relationship between the control factors and response can be further understood by these plots. Fig. 2 shows the 3D response surface plot relationship between the mill speed (*A*) and the ball size (*B*). Fig. 3 shows the 3D response surface plots relationship between the mill speed (*A*) and the grinding time (*C*). Fig. 4 shows the 3D response surface plot relationship between the ball size (*B*) and the grinding time(*C*). The all 3D response surface plots demonstrate that the all operating parameters have an important effect on d_{80} size.

4.3. Analysis of variance

The analysis of variance (ANOVA) is used to investigate which control factors significantly affect the quality characteristic. It is accomplished by separating the total variability of the S/N ratios, which is measured by sum of the squared deviations from the total mean S/N ratio, into contributions by each of the control factors and the errors. The *F* value for each control factors was calculated as shown Table 4. Usually, when $F > 4$ it means that the control factor showed a significant effect on the quality characteristic. For calcite grinding, the calculated values of *F* depicts that all control factors namely mill speed (*A*), ball size (*B*) and grinding time (*C*) have a high significant effect on calcite grinding process.

4.4. Confirmation tests

Once the optimal level of the control factors has been selected, the final step is to predict and verify the improvement of the quality characteristic using the optimal level of the control factors. The estimated S/N ratio $(\hat{\eta}_i)$ using the optimal level of the control factors can be calculated as [11-14]:

$$\hat{\eta}_i = \eta_m + \sum_{i=1}^{n} (\tilde{\eta} - \eta_m) \tag{2}$$

where η_m is the total mean S/N ratio, $\tilde{\eta}$ is the mean S/N ratio at the optimal level and n is the number of the main control factors that affect the quality characteristic.

Table 3. S/N response table for d_{80} size

Symbol of control factors	Level 1	Level 2	Level 3	Level 2	Level 2	Level2	Delta	Rank
A	-39.67	-39.05	-36.54*	-37.99	-37.57	-37.93	3.13	1
B	-36.72*	-38.58	-39.07				2.34	3
C	-39.55	-37.96	-36.86*				2.69	2

Optimal level

Table 4. Analysis of variance (ANOVA) for S/N ratios

Symbol of control factor	Degree of Freedom (DF)	Sum of squares(SS)	Mean of squares(MS)	*F* characteristics	*P*
A	**5**	**18.363**	**3.673**	**6.76**	**0.009**
B	**2**	**18.348**	**9.174**	**16.89**	**0.001**
C	**2**	**21.867**	**10.933**	**20.12**	**0.001**
Error	**8**	**4.346**	**0.543**		
Total	**17**	**62.924**			

Table 5. Confirmation tests results and comparison with predicted values

Run	**Optimal control factors**			**Predicted values**		**Verification test results**		**Difference**	
	A	***B***	***C***	**S/N (dB)**	**d_{80} (μm)**	**S/N (dB)**	**d_{80} (μm)**	**Δd_{80}**	**ΔS/N**
19	**3**	**1**	**3**	**-33.87**	**49**	**-33.63**	**48**	**1**	**0.24**
20	**3**	**1**	**3**	**-33.87**	**49**	**-34.15**	**51**	**2**	**0.28**

The estimated S/N ratio using the optimal grinding factor for calcite grinding can then be obtained and the corresponding d_{80} size can also be calculated by using Eqs. (1)-(2). Fig. 5 shows the actual values versus the predicted values for d_{80} size. In this figure, as the data points close to the diagonal line (R^2 value of 0.92) indicating a good agreement between predicted values and the actual data points.

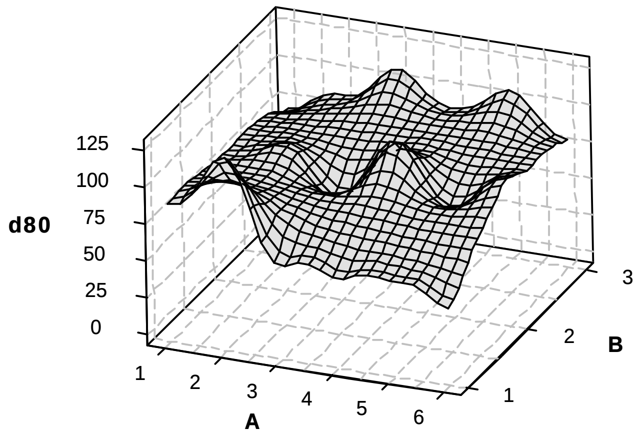

Fig.2. Response surface plots showing the effect of mill speed (*A*) and ball size (*B*) on d_{80} size.

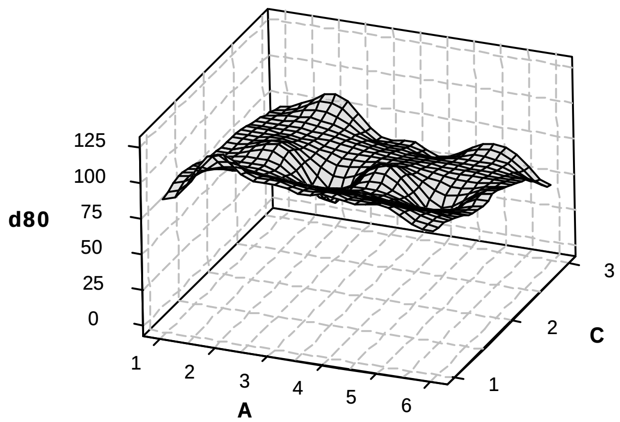

Fig.3. Response surface plots showing the effect of mill speed (*A*) and grinding time (*C*) on d_{80} size.

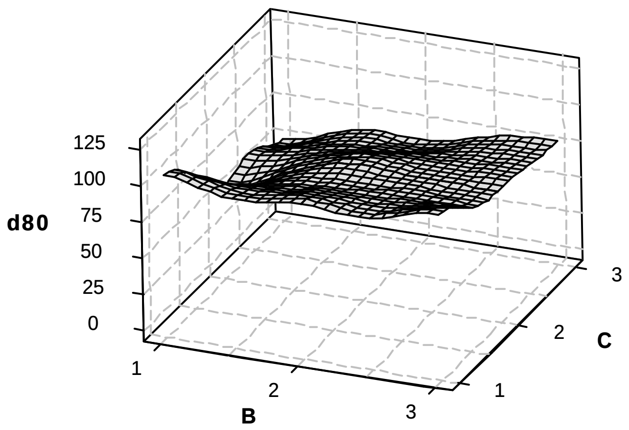

Fig.4. Response surface plots showing the effect of ball size (*B*) and grinding time (*C*) on d_{80} size.

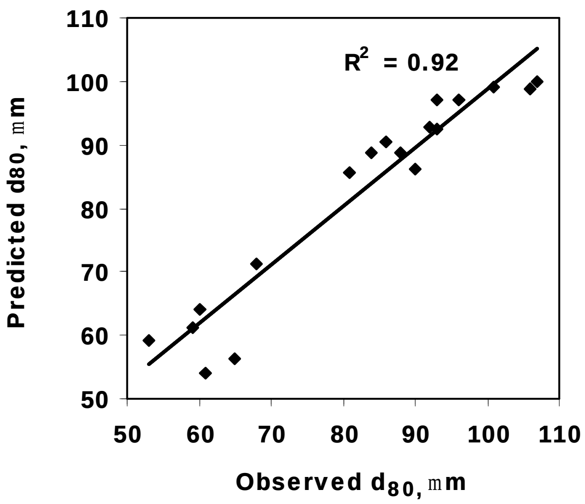

Fig.5. Predicted versus observed for d_{80} size

Furthermore, two extra grinding tests were conducted to verify the results using the optimal level of the control factors, which are presented in Table 5. From this table, it can be seen that the difference between both for d_{80} and S/N ratio is in all cases within the reasonable limit.

5. Conclusions

The Taguchi method was adopted to investigate the effect of mill speed, ball size and grinding time on calcite grinding. The optimal process control factors which minimize the d_{80} size of product were the mill speed (%Critical) at 3 level (%70), ball size at level 1 (20 mm) and the grinding time at level 3 (30 min) with the prediction of 49 µm d_{80} size. The mill speed has stronger effect on the calcite grinding process followed by the grinding time and the ball size. The analysis of variance (ANOVA) was used to investigate which control factors significantly affect the quality characteristic. For calcite grinding, the calculated values of F from ANOVA table (see Table 4) depicts that the mill speed (A), the ball size (B) and the grinding time (C) have a high significant effect on grinding process.

In order to verify the predictive capacity of the model, two extra confirmation tests were conducted at the optimal control factors. The difference between confirmation tests results and predicted values for d_{80} size is in all cases within the reasonable limit (see Table 5). The predicted d_{80} using the optimal control factors for calcite grinding could be calculated. A good agreement between the predicted and actual d_{80} values was observed at 95% confidence level. From the results obtained, it is evident that Taguchi method is an effective tool in designing the experiment for optimization of the calcite grinding.

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