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OPTIMIZATION OF CLINKER GRINDING USING THE TAGUCHI METHOD

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Abstract

The purpose of this study is to demonstrate how the application of the Taguchi method can be used to optimize clinker grinding. In order to observe the influencing degree of contol factors in a dry grinding system, three control factors namely ball size, fractional ball charge and speed of rotation, and each factor at three levels on product 80% passing size (d_{80}) were studied and optimized. The experimental conditions were studied in the range of 13-45 mm for ball dimeter, 0.15-0.25 of fractional ball charge and 60-80% of critical speed for mill rotation. A three level orthogonal array design with nine experimental runs was selected. The Taguchi method includes regression of a model to the data, to predict an optimal combination of operating parameters. The predicted optimum point was determined and further tests confirmed the validity of the prediction. The ball size was found to have the largest effect on clinker grinding.

Keywords: grinding, comminution, process optimization

1. Introduction

Grinding is a highly energy consuming process. According to statistics, the energy consumption of the coal and cement grinding processes in power and cement plants accounted for 7.26% of all nationwide industrial power consumption in 2003 [1]. Of all dry grinding applications, cement production is of significant ratio. The estimate for the world energy consumption for cement production is 18.7TWh which is approximately 0.02% of total world energy consumption per year [2]. In the cement industry, the clinker grinding step consumes about one-third of the power required to produce each ton of cement. This refers to an average specific power consumption of 57 kWh/t [3] and specific carbon dioxide emissions intensity for electricity generation of 9.1 kg CO_2 per ton [4]. Considering these factors, 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].

Thus, in recent years, 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]. In this context, a large number of experimental investigations linking cement or clinker 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 variables if optimum performance is to be achieved. Many variables can affect the efficiency and productivity of a dry grinding system, such as operational speed, fractional ball filling, feed rate, hardness of the feed material and feed size. Optimizing these variables in the grinding systems is an important step in minimizing the cost of production [6-7]. The Taguchi method is an efficient problem-solving tool, which can upgrade/improve the performance of the product, process, design, and system with a significant reduction in experimental time and cost [8]. This method combines the experimental design theory and the concept of quality loss function, and has been used to carry out a robust design of processes and products and solving several complex problems in manufacturing industry [9]. Further, this technique determines the parameter which has the most effect on overall performance.

The purpose of this study is to demonstrate how the application of Taguchi method can be used to develop an effective optimization process for clinker grinding. An optimization of clinker grinding based on ball mill using the Taguchi method with multiple performance characteristics is proposed.

2. Experimental material and grinding tests

Dry grinding experiments on clinker were carried out using a laboratory batch ball mill. The stainless steel mill has 209 mm diameter and 175 mm length with six lifters bars. Critical rotation speed (N_C) is 102 rpm for the ball mill. For all experiments, the clinker sample obtained from Lafarge Sivas Plant (Turkey) was prepared using a √2 sieve series to be used as the feed charge. The clinker feed weight was held constant at 300 g, which was -2000 μm and had 930 μm of the d_{80} size. The grinding time was 20 min 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. The d_{80} size, which does facilitate routine control of the grinding circuit, of the products was determined by drawing the cumulative undersize curve. Dry sieving technique was used to produce data for these curves.

3. Experimental design and Taguchi method

The experiments were carried out to analyze the influence of control factors on clinker grinding process, the code and levels of three control factors namely ball size, fractional ball charge and speed of rotation were shown in Table 1. This table shows that the experimental plan had three levels. A standard Taguchi orthogonal array with notation L_9 was chosen. Maintaining these control factors, the other operating conditions were kept constant at those mentioned above.

After the experiments were conducted, the optimal control factors configuration within the experiment design must be determined. To analyze the results, Taguchi technique utilizes a statistical measure of performance called signal-to-noise (*S/N*) ratio approach to measure the quality characteristic deviating from the desired value. It is also used the *S/N* ratio approach instead of the average value to convert the experimental results into a value for the evaluation characteristic in the optimum parameter analysis. The *S/N* ratio (η) is quoted in dB units and it can be defined as [10-13];

$$\eta = -10 \log(M.S.D.) \tag{1}$$

where *M.S.D.* is the mean-square deviation for the output characteristic. The *S/N* ratio characteristics can be divided into three types: the nominal-the better, the smaller-the better, and the higher-the better when the quality characteristics are continuous for engineering analysis [14]. Whatever the type of quality 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 clinker grinding process. The *S/N* ratio for each level of control factors was computed based on the *S/N* analysis. The *M.S.D.* for the smaller-the better quality characteristic can be expressed as:

$$M.S.D. = \frac{1}{n}\left(\sum_{i=1}^{n} y_i^2\right) \tag{2}$$

where y_i is the value of d_{80} size for the i^{th} test, n is the number of repetitions done for an experimental combination (here n=3). Because -log is a monotone decreasing function, it implies that highest *S/N* value desire for optimization. Thus, the *S/N* values are calculated by exploiting Eqs.(1-2). The d_{80} size values of products under the process parameters corresponding ball size (*A*), fractional ball charge (*B*) and speed of rotation (*C*) based on L_9(3**3 orthogonal arrays of Taguchi and their *S/N* ratio values are listed in Table 2.

Table 1. Process control factors and their levels

Control factors	Symbol	Level 1	Level 2	Level 3
Ball size	A	small[1]	middle[2]	big[3]
Fractional ball charge	B	J= 0.15	J= 0.20	J= 0.25
Speed of rotation	C	60% of N_C	70% of N_C	80% of N_C

[1] Equal-weight balls of 13mm, 20mm and 20mm diameter
[2] Equal-weight balls of 25mm, 30mm and 35mm diameter
[3] Equal-weight balls of 35mm, 40mm and 45mm diameter

Table 2. Experimental lay out and results of grinding process

Exp no.	Control factors A	B	C	d_{80} (μm)	S/N ratios (dB)
1	1	1	1	175	-44.8608
2	1	2	2	124	-41.8684
3	1	3	3	142	-43.0458
4	2	1	2	123	-41.7981
5	2	2	3	105	-40.4238
6	2	3	1	128	-42.1442
7	3	1	3	121	-41.6557
8	3	2	1	102	-40.1720
9	3	3	2	98	-39.8245

4. Results and discussion

4.1. Analysis of control factor

By opting for Taguchi method, the number of experiments to be conducted was reduced to nine, instead of the actual 27 experiments for chosen three parameters with three levels in this work. For dry clinker 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 the 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 from level 1 to level 3. 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 determined from the *S/N* response graphs in Fig.1 for this process. The *S/N* ratios of each experimental run were calculated based on the Eqs. (1-2). 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 clinker grinding are shown in Table 3. The rank (1) in this table indicates that the ball size factor has strongest effect on the process followed by rank (2) the fractional ball charge, which has smallest effect, while rank (3) has minimum effect on the process. Response surface analysis (Figs.2-4) also indicates the minimum d_{80} size at level 3 of ball size, at level 2 of fractional ball charge and speed of rotation.

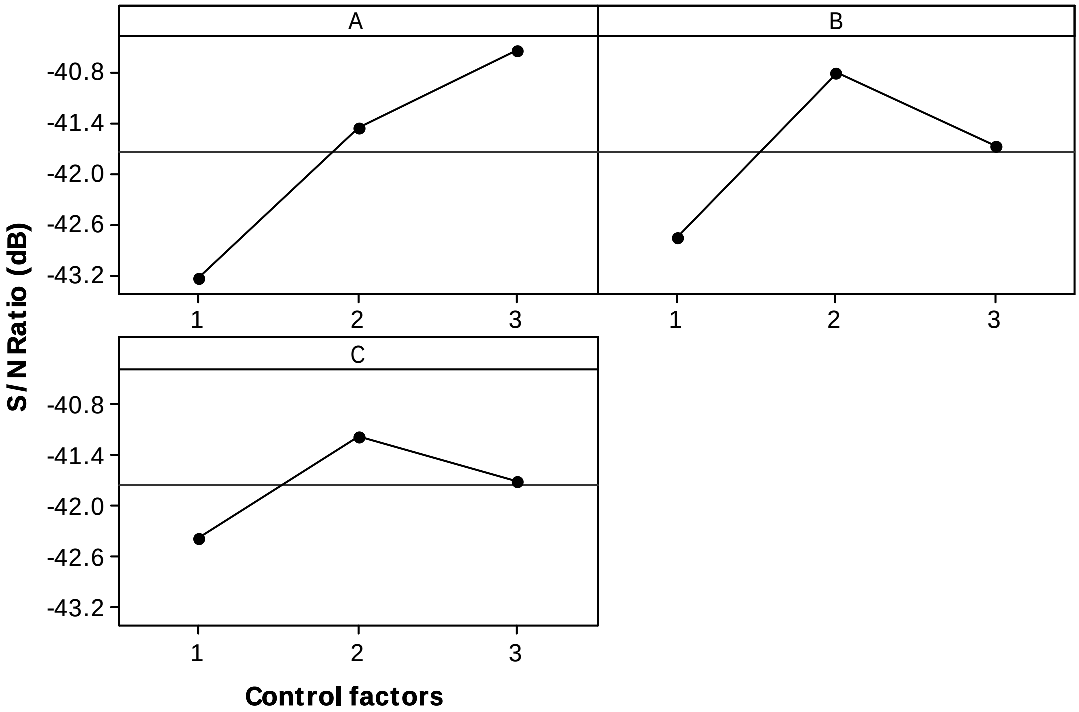

Fig.1. Main effect graphs for S/N ratio

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

Symbol of control factors	Level 1	Level 2	Level 3	Delta	Rank
A	-43.26	-41.46	-40.55*	2.71	1
B	-42.77	-40.82*	-41.67	1.95	2
C	-42.39	-41.16*	-41.71	1.23	3

*Optimum level

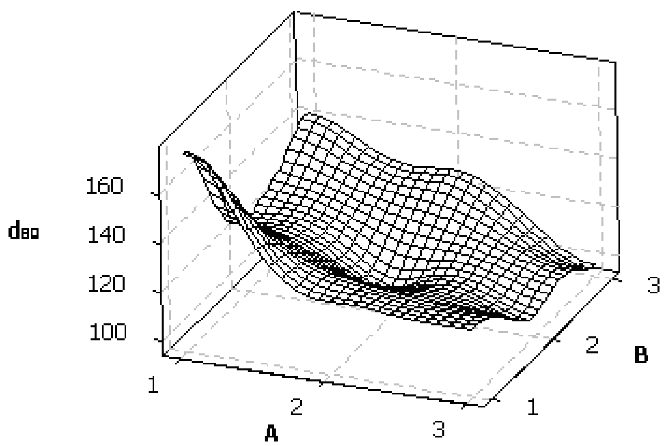

Fig.2. Response surface plots showing the effect of ball size (*A*) and fractional ball charge (*B*) on d_{80} size at level 2 of speed of rotation (*C*)

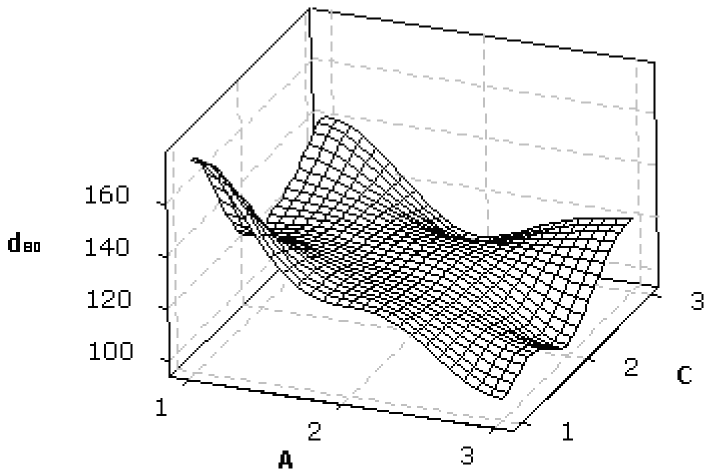

Fig.3. Response surface plots showing the effect of ball size (*A*) and speed of rotation (*C*) on d_{80} size at level 2 of fractional ball charge (*B*)

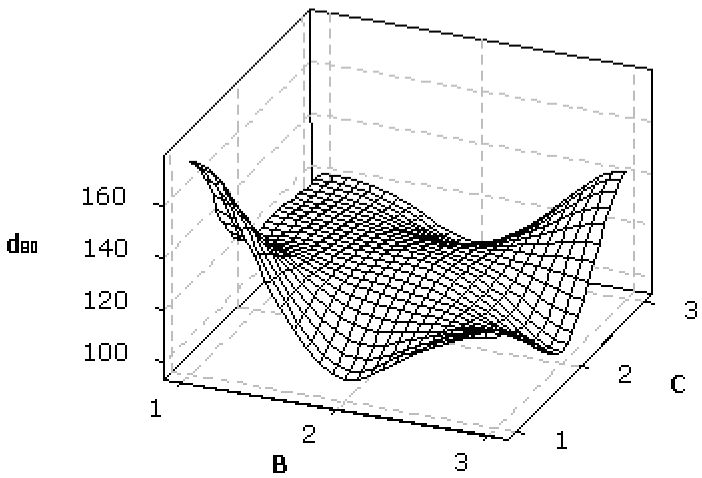

Fig.4. Response surface plots showing the effect of fractional ball charge (*B*) and speed of rotation (*C*) on d_{80} size at level 2 of ball size (*A*)

4.2. 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 clinker grinding, the calculated values of *F* depicts that ball size (*A*) and fractional ball charge (*B*) have a very high significant effect, and speed of rotation (*C*) has a high significant effect on grinding process. The last column of Table 4 also indicates the percentage of each factor contribution (*P*) on the total variation, thus exhibiting the degree of influence on result. It might be observed in this table that ball size factor (P = 58.48%), fractional ball charge (P = 29.43%) and speed of rotation (P = 11.67%) had a significant influence on the grinding system.

Table 4. Analysis of Variance for S/N ratios

Symbol of control factor	Degree of Freedom (DF)	Sum of squares(SS)	Mean of squares(MS)	*F* characteristics	*P*	Contributions (%)
A	2	11.4000	5.69998	137.31	0.007	58.48
B	2	5.7357	2.86783	69.09	0.014	29.43
C	2	2.2740	1.13700	27.39	0.035	11.67
Error	2	0.0830	0.04151			
Total	8	19.4926				

4.3. 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 [11-12, 14-15]:

$$\hat{\eta}_i = \eta_m + \sum_{i=1}^{n} (\tilde{\eta} - \eta_m) \tag{3}$$

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.

The estimated *S/N* ratio using the optimal grinding factor for clinker grinding can then be obtained and the corresponding d_{80} size can also be calculated by using Eqs. (1-3). Fig. 5 shows the actual values versus the predicted values for d_{80} size. In this figure, as the data points very close to the diagonal line (R^2 value of 0.99) indicating a good agreement between predicted values and the actual data points.

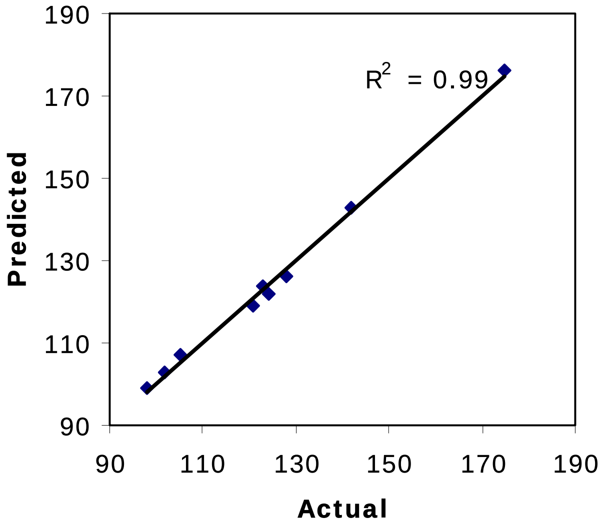

Fig.5.Predicted versus actual for d_{80} size

Table 5. Confirmation tests results and comparison with predicted values

Exp no.	Opt. parameters			Predicted values		Verification test results		Difference	
	A	B	C	d_{80} (μm)	S/N (dB)	d_{80} (μm)	S/N (dB)	Δd_{80}	ΔS/N
10	3	2	2	89	-39.0262	91	-39.1808	2	0.1546
11	3	2	2	89	-39.0262	93	-39.3697	4	0.3435

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 ball size, fractional ball charge and speed of rotation on clinker grinding. The optimal process control factors which minimize the d_{80} size of product were the ball size at 3 level (big size), fractional ball charge at level 2 (J = 0.20) and the speed of rotation at level 2 (70% of N_C). The ball size had the greatest effect and its contribution was 58.48%, followed by the fractional ball charge its contribution was 29.43% and the speed of rotation had a lower effect its contribution was 11.67% on quality characteristic. The predicted d_{80} using the optimum control factors for clinker grinding could be calculated. A good agreement between the predicted and actual d_{80} values was observed at 95% confidence level. This study demonstrates that Taguchi Method could be successfully applied for optimizing clinker grinding at laboratory scale and that it is the economical way of obtaining maximum amount of information in a short period of time and with the least number of experiments.

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