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Grinding analysis of Indian coal using response surface methodology

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Abstract The present work discusses a systematic approach to model grinding parameters of coal in a ball mill. A three level Box–Behnken design combined with response surface methodology using second order model was applied to the experiments done according to the model requirement. Three parameters ball charge (numbers 10–20), coal content (100–200 g) and the grinding time (4–8 min) were chosen for the experiments as well as for the modeling work. Coal fineness is defined as the d_{80} (80 % passing size). A quadratic model was developed to show the effect of parameters and their interaction with fineness of the product. Three different sizes (4, 1 and 0.65 mm) of Indian coal were used. The model equations for each fraction were developed and different sets of experiments were performed. The predicted values of the fineness of coal were in good agreement with the experimental results (R^2 values of d_{80} varies between 0.97 and 0.99). Fine size of three different coal sizes were obtained with larger ball charge with less grinding time and less solid content. This work represents the efficient use of response surface methodology and the Box–Behnken design use for grinding of Indian coal.

1 Introduction

The consumption of solid fossil fuel is gaining importance in world energy production. There has been an increase in studies on coal since it is an alternative to petrol and has a high reserve. The pulverized coal injection is used to obtain high heat capacity and high burning efficiency in thermal reactors and boilers based on coal. For this purpose, coals are ground at a micron size and then sent to boilers to achieve maximum calorific value. Comminution of coal is essential for effective utilization through combustion, carbonization, gasification and/or beneficiation (Prasher 1987). Preheating a coal in an oven has been shown to

reduce grind strength, although it is unlikely that this would be an economically viable method, at least not through associated energy requirements (Harrison and Rowson 1997). The grindability of coal is an important practical and economical property to coal handling and utilization aspects. Thus engineering experiments wish to find the grinding conditions under which a certain process reaches its response optimum. The optimum could be either a maximum or a minimum of a function of the design parameters. One of the methodologies is the surface response methodology (Kwak 2005). Grinding media charge ratio in a conventional grinding system is approximately 40 %. This leads to a better delivery of the grinding energy (Kincl et al. 2005; Lester et al. 2005; Barranco et al. 2006). Grinding in a ball mill has shown that the ball charge has a significant effect on the product fineness for same specific energy consumption and increases power draws of the mill linearly (Tuzun 1994 and Jankovic 2001). The ball size should be just heavy and large so that the charge should be grinded efficiently. In the present work the ball size is kept constant and these are considered to be

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efficient for the grinding media. In the grinding of Turkish coal and ore, the charge ratio, Bond work index and the ball diameter were taken as the variables in the experiments however, time of grinding is also a significant parameter in the grinding experiments (Aslan and Cebeci 2007; Edadnejad et al. 2013).

The objective of the present work is to establish the optimum conditions for the grinding of an Indian coal. The grinding of coal may depend on several parameters however, in the present study the grinding time, charge content and number of balls in a ball mill are considered as parameters. These three parameters are most important parameters in grinding of coal which were ignored in previous works. According to the requirement of the response surface methodology, experiments were done for three different size fractions of coal. Box-Behnken design to model the experimental results was used.

2 Materials and methods

Initially 7–10 cm size of Indian coal was crushed in a jaw crusher and roll crusher successively to prepare the feed for the ball mill. Three different sizes, 80 % passing of specified screen (d_{80}) for grinding test of coal particles were chosen before milling in a ball mill. The d_{80} sizes of coal particles of feed were 4, 1, and 0.65 mm. After grinding d_{80} of these sizes were 1.65, 0.7, 0.25 mm. Grinding tests were performed in a laboratory scale ball mill of 37.5 cm long and 27 cm diameter. The size of the balls used were of 2.5 cm diameter. The rotation speed of the ball mill was kept adequate for the charge to mix and impact together. A proximate analysis of coal is also performed before the actual experiments, Table 1. The density of the coal used was 1.38 gm/cm^3.

3 Response surface methodology

Response surface methodology (RSM) is a collection of statistical and mathematical system for the analysis of complex engineering and scientific problems. Using this technique one can evaluate the effect of different important parameters on response.

The design procedure is as follows (Gunaraj and Murugan 1999; Aslan and Cebeci 2007; Edadnejad et al. 2013):

(1) Designing of a series of experiments for adequate and reliable measurement of the surface response of interest.

(2) Developing a mathematical model of the second-order response surface with the best fittings.

(3) Finding the optimal set of experimental parameters that produce a maximum or minimum value of response.

(4) Representing the direct and interactive effects of process parameters through two and three dimensional (3D) plots.

If all the independent variables are measurable, the response of the surface methodology can be expressed as

$$y = f(x_1, x_2, x_3, \ldots, x_n) \tag{1}$$

where y is response of the system.

A Box–Behnken design with three levels was utilized to evaluate the effect of parameters on fineness of coal. So these three independent parameters were coded at three levels that is $+1$, 0, and -1 with same step size, where $+1$ represents the maximum value, 0 represents to the center, and -1 represents the minimum value of each parameter, which are considered for analysis. Within the present research framework, the discussion is focused on the effect of number of balls (A), amount of feed charged (B), and grinding time (C) on the fineness of coal using a Box-Behnken design. Table 2 shows the experimental design matrix with coded and actual values of parameters A, B, and C.

To find the optimum conditions, a quadratic model is used to relate fineness of coal to independent parameters. This model can be written as:

$$y = \alpha_0 + \sum_{j=1}^{n} \alpha_j x_j + \sum_{j=1}^{n} \alpha_{jj} x_j^2 + \sum_{j=1}^{n-1} \sum_{k=2}^{n} \alpha_{jk} x_j x_k + \delta \tag{2}$$

The set of regression coefficients α's are unknown and estimated by least squares. In vector–matrix, the equation for least square fit is given by:

$$Y = X\alpha + \delta \tag{3}$$

where Y is defined as the measured values and X to be a matrix of independent variables. Regression coefficients α

Table 1 Proximate analysis of a typical Indian coal

Parameter	Dry basis (%)
Moisture	6.01
Ash	39.48
Volatile matter	18.65
Fixed carbon	35.6

Table 2 The level of variables in Box-Behnken design

Parameter	Low (−1)	Center (0)	High (+1)
A (Grinding time)	4	6	8
B (Number of balls)	10	15	20
C (Amount of feed)	100	150	200

is solved by premultiplying by the non singular regression matrix transpose X'

$$\beta = (X'X)^{-1}X'Y \tag{4}$$

where X' is the transpose of the matrix X and $(X'X)^{-1}$ is the inverse of the matrix $X'X$. Applying the present variables in Eq. (2), the equation will expand in the form as follows:

$$y_{d_{80}} = \alpha_0 + \alpha_1 A + \alpha_2 B + \alpha_3 C + \alpha_4 AB + \alpha_5 AC + \alpha_6 BC + \alpha_7 A^2 + \alpha_8 B^2 + \alpha_9 C^2 + \delta_i \tag{5}$$

where y is response (fineness of coal of 80 % passing), and A, B, and C are the independent parameters. α_0 is the constant coefficient, α_1, α_2, and α_3, are the coefficients for linear effect, α_4, α_5, and α_6, are the coefficients for interaction effect, α_7, α_8, and α_9, are the coefficients for quadratic effect, and δ_i is the error.

Response surface methodology uses the experimental data points of the design matrix to a proposed model and the unknown coefficients. To find the minimum number of experimental run required for Box-Benhken design one can use equation given below:

$$N = 2N_f(N_f - 1) + C_p \tag{6}$$

where N_f is the number of parameters used to fit the model, and C_p is the number of the central points. To evaluate the coefficient values 15 experiments were carried out for each particle size and total 45 experiments were done for three different particle size according to the Box–Behnken design. Figure 1 shows the distribution of the experimental data points in the graphical form. Accordingly experiments were designed and Table 3 shows the design matrix of the experiments for three different particle sizes.

4 Result and discussion

There were 15 experiments which were done for each coal particle size as listed in Table 4. Model equations basically represent the relationship between fineness as d_{80} and
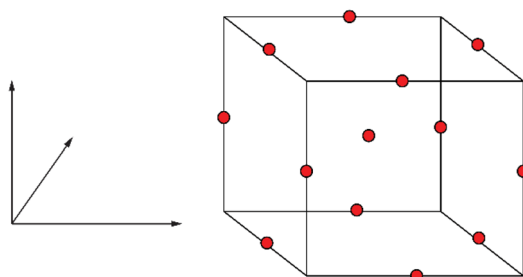

Fig. 1 The graphical representation of a three parameters Box-Behnken design

Table 3 Design matrix with coded and actual design parameters

Run no.	Coded values			Actual values		
	A	B	C	A	B	C
1	+1	0	−1	8	15	100
2	0	+1	+1	6	20	200
3	+1	−1	0	8	10	150
4	−1	0	−1	4	15	100
5	−1	+1	0	4	20	150
6	0	0	0	6	15	150
7	+1	+1	0	8	20	150
8	0	−1	−1	6	10	100
9	−1	0	+1	4	15	200
10	0	0	0	6	15	150
11	−1	−1	0	4	10	150
12	+1	0	+1	8	15	200
13	0	−1	+1	6	10	200
14	0	0	0	6	15	150
15	0	+1	−1	6	20	100

different experimental design parameters. For three different size fractions of coal using Box-Behnken design were obtained as given below:

For $-1.65 + 4$ mm size fraction:

$$y1_{d_{80}} = 781.25 + 9.375A + 43.12B + 12.43C + 3.12AB - 0.4375AC - 4.34 \times 10^{-16}BC - 3.12A^2 - 2.75B^2 - 0.0225C^2 \tag{7}$$

For $-0.7 + 1$ mm size fraction:

$$y2_{d_{80}} = -30 + 72.5A + 44B + 5.27C - 2.25AB - 0.1AC + 7 \times 10^{-2}BC - 3.43A^2 - 1.65B^2 - 0.0145C^2 \tag{8}$$

For $-0.25 + 0.65$ mm size fraction:

$$y3_{d_{80}} = 295.62 - 39.68A + 1.12B + 1.67C - 0.37AB - 0AC + 0BC + 2.65A^2 - 0.075B^2 - 0.002C^2 \tag{9}$$

Using the parameters defined in Table 2, the experimental values were obtained by performing experiments and the predicted values were calculated using Eqs. (7–9) in Table 3. From the experimental results listed in Table 4 and Eq. (5), the second order response functions representing d_{80} can be expressed in model equations. Table 5 shows the validation of model developed by using Box-Behnken design with experimental values of three different size fractions. The responses of three different size fraction of fineness can be calculated by Eqs. (7–9) for different variables defined.

Table 4 Actual and coded values of three parameters for three responses

Run no.	Parameter			Experimental values of responses		
	A (min)	B	C (g)	$y1_{d_{80}}$ (µm)	$y2_{d_{80}}$ (µm)	$y3_{d_{80}}$ (µm)
1	8(+1)	15(0)	100(-1)	1700	770	250
2	6(0)	20(+1)	200(+1)	1900	880	350
3	8(+1)	10(-1)	150(0)	1900	875	325
4	4(−1)	15(0)	100(−1)	1800	800	300
5	4(−1)	20(+1)	150(0)	1875	860	340
6	6(0)	15(0)	150(0)	2000	900	320
7	8(+1)	20(+1)	150(0)	1750	725	275
8	6(0)	10(−1)	100(−1)	1850	800	275
9	4(−1)	15(0)	200(+1)	2250	950	400
10	6(0)	15(0)	150(0)	2000	900	320
11	4(−1)	10(−1)	150(0)	2150	920	375
12	8(+1)	15(0)	200(+1)	1975	880	350
13	6(0)	10(−1)	200(+1)	2100	910	375
14	6(0)	15(0)	150(0)	2000	900	320
15	6(0)	20(+1)	100(−1)	1650	700	250

Table 5 Comparison of experimental and predicted d_{80} values

$y1_{d_{80}}$ (µm)		$y2_{d_{80}}$ (µm)		$y3_{d_{80}}$ (µm)	
Experimental	Predicted	Experimental	Predicted	Experimental	Predicted
1700	1728	770	756	250	250
1900	1925	880	866	350	355
1900	1896	875	875	325	328
1800	1828	800	806	300	304
1875	1878	860	860	340	348
2000	2000	900	900	320	325
1750	1753	725	745	275	286
1850	1825	800	813	275	281
2250	2221	950	963	400	411
2000	2000	900	900	320	325
2150	2146	920	900	375	374
1975	1946	880	873	350	358
2100	2131	910	916	375	389
2000	2000	900	900	320	325
1650	1618	700	693	250	248

The actual and predicted values of three different size fractions are depicted in Figs. 2, 3 and 4. Predicted values are quite close to the experimental values and the values of R^2 are 0.98, 0.97 and 0.99 for −1.65 + 4 mm size fraction, −0.7 + 1 mm size fraction and −0.25 + 0.65 mm size fraction, respectively.

In order to understand the effect of operating parameters on the d_{80} the results are shown in Figs. 5, 6, 7, 8, 9, 10, 11, 12 and 13. Figures 5, 6 and 7 show the 3D response surface plot for coarse size fraction (−1.65 + 4 mm). Figure 5 shows the effect of number of balls and grinding time on fineness. The grinding time and the number of balls on the coarse particle size have positive effect as the increased grinding time and increased number of balls enhance the fineness. However, individual effect of balls can also be observed as for less time increasing number of balls results in increased fineness. Figure 6 shows the effect of number of balls and amount of feed on response. The decreased
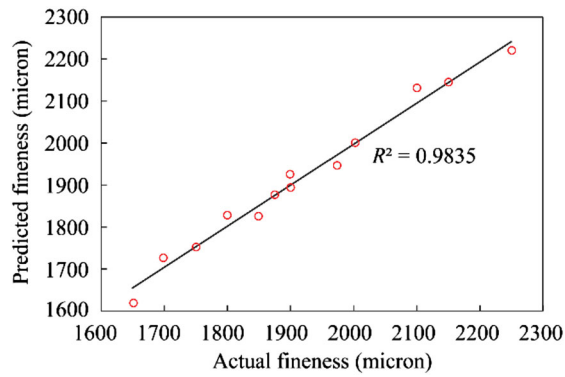
Fig. 2 Experimental values versus predicted values of fineness for size fraction for $-1.65 + 4$ mm size fraction
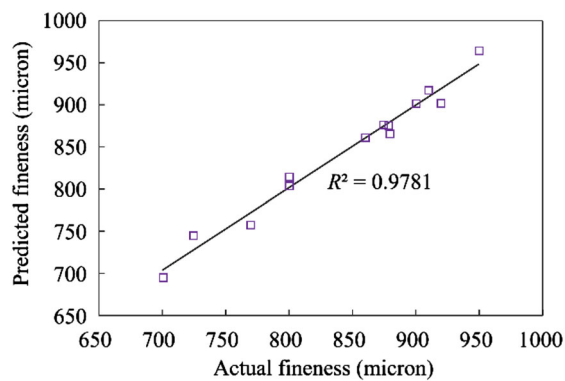

Fig. 3 Experimental values versus predicted values of fineness for size fraction for $-0.7 + 1$ mm size fraction
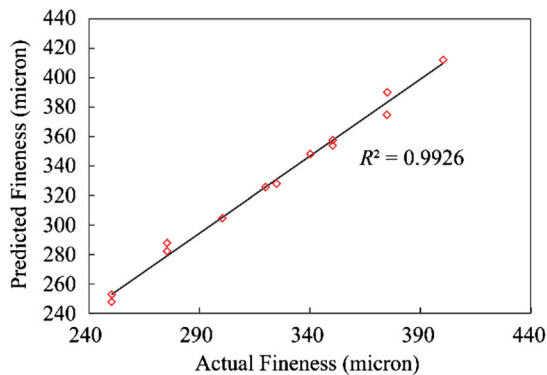

Fig. 4 Experimental values versus predicted values of fineness for size fraction for $-0.25 + 0.65$ mm size fraction

amount of feed and increased number of balls are in favor of fineness. Figure 7 shows the effect of grinding time and amount of feed. It is revealed that increasing grinding time and decreasing amount of feed produces fine material.

Figures 8, 9 and 10 show the effect of different parameters on response in contour plot for the $-0.7 + 1$ mm size fraction. Figure 8 shows that decrease
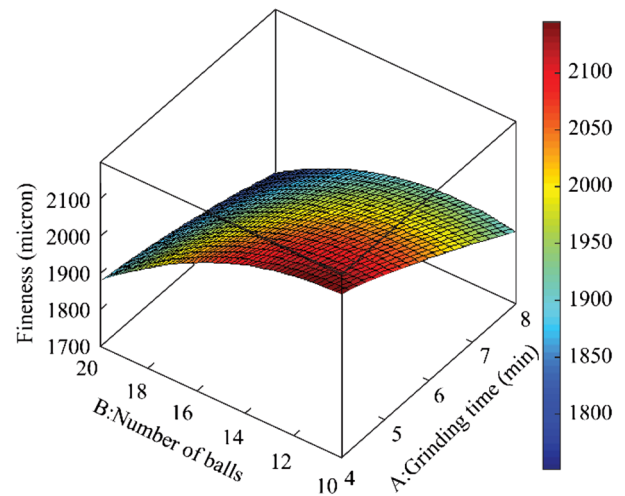
Fig. 5 Response surface of fineness of coal to the variation of number of balls and grinding time at average amount of feed of 150 gm for $-1.65 + 4$ mm size fraction
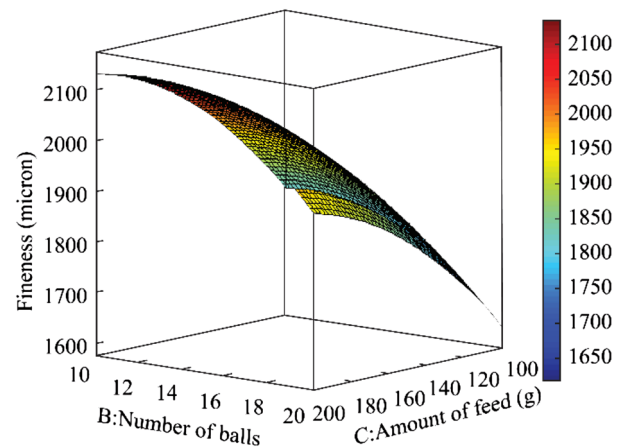
Fig. 6 Response surface of fineness of coal to the variation of number of balls and amount of feed at average grinding time of 6 min for $-1.65 + 4$ mm size fraction

in amount of feed and increase in grinding time more fine material can be produced. This may be due to more impact of balls will be observed by the feed which results in more fine material. Figure 9 shows that number of balls used in grinding plays an important role. Increasing number of balls can produce finer particles. On the other hand if the fineness is fixed one can reduce the grinding time and energy can be saved. Figure 10 shows the effect of number of balls and grinding time on d_{80}. It is clear from figure that number of balls on fineness has dominant effect than grinding time. With more number of balls and less grinding time one can produce more fine powder. The figure reflects that process will be inefficient if ball mill is operated between 11 and 16 number of balls and 4 to 5.9 min grinding time.
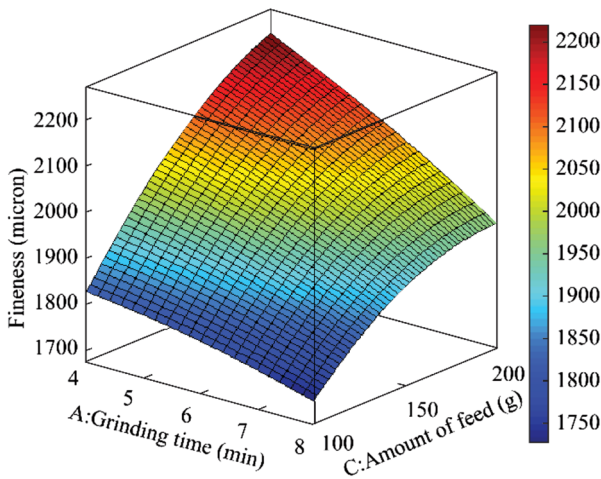
Fig. 7 Response surface of fineness of coal to the variation of grinding time and amount of feed at average number of balls of 15 for $-1.65 + 4$ mm size fraction
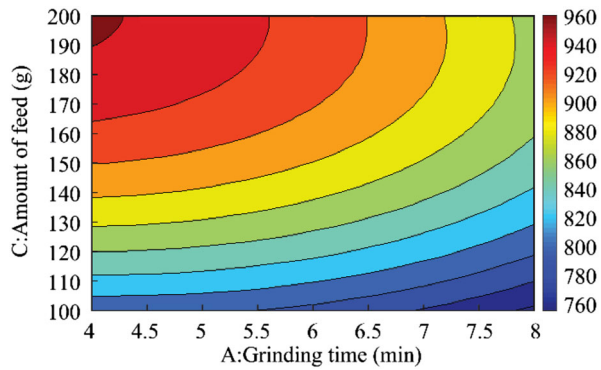

Fig. 8 Contour plot response surface of fineness of coal to the variation of grinding time and amount of feed at average number of balls of 15 for $-0.7 + 1$ mm size fraction
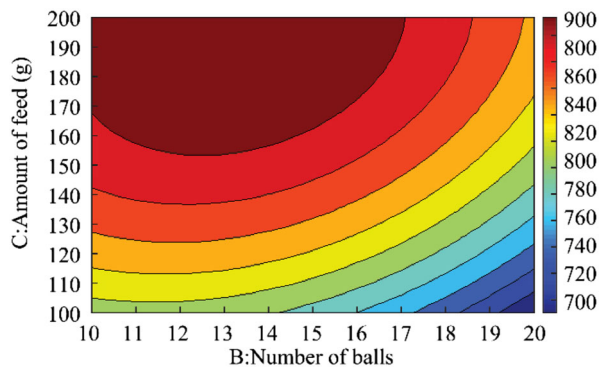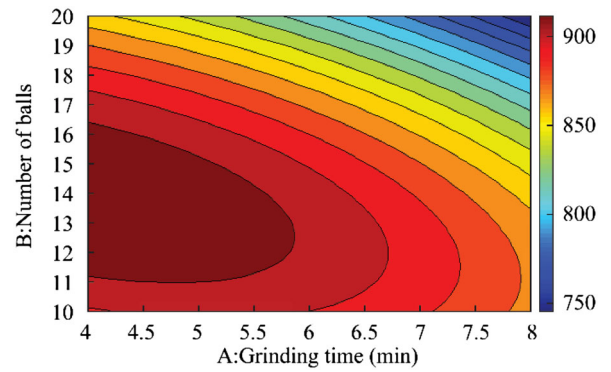

Fig. 9 Contour plot response surface of fineness of coal to the variation of number of balls and amount of feed at average grinding time of 6 min for $-0.7 + 1$ mm size fraction

Figures 11, 12 and 13 show the contour and 3D surface plot response of $-0.25 + 0.65$ mm size fraction. These figures show the similar effect of number of balls, amount

Fig. 10 Contour plot response surface of fineness of coal to the variation of number of balls and grinding time at average amount of feed of 150 gm for $-0.7 + 1$ mm size fraction
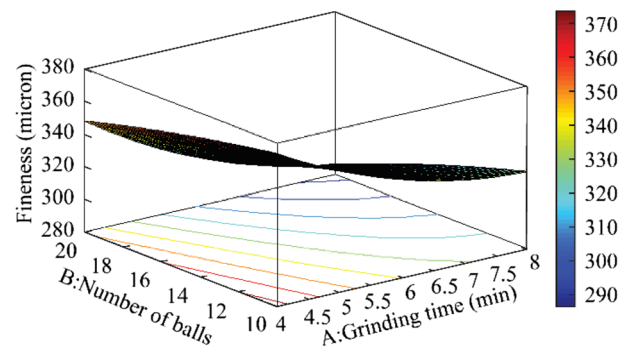

Fig. 11 Contour and surface plot of response surface of fineness of coal to the variation of number of balls and grinding time at average amount of feed of 150 gm for $-0.25 + 0.65$ mm size fraction
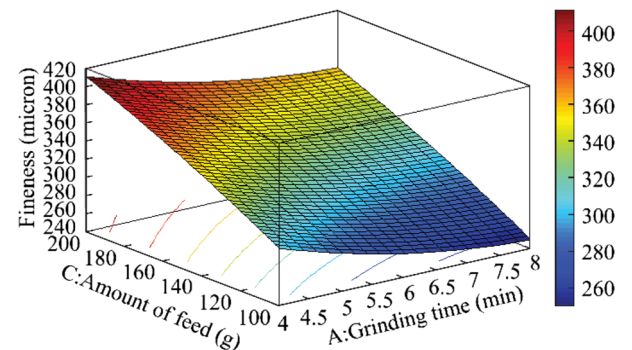

Fig. 12 Contour and surface plot of response surface of fineness of coal to the variation of number of balls and amount of feed at average grinding time of 6 min for $-0.25 + 0.65$ mm size fraction

of feed and grinding time on fineness as discussed for the other two size fractions. These contour plots can help finding fineness of coal particles at any zone of the experimental region. The results concludes that the small amount of feed stayed longer will result in fine product.
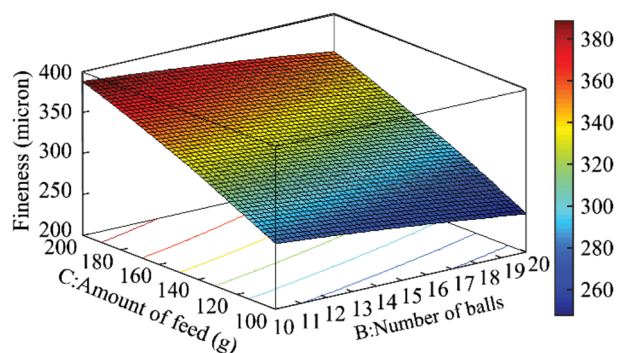
Fig. 13 Contour and surface plot of response surface of fineness of coal to the variation of grinding time and amount of feed at average number of balls of 15 for $-0.25 + 0.65$ mm size fraction

The optimal levels of different parameters studied like number of balls, grinding time, and amount of feed could provide a beneficial information to calculate the power requirement to grind a particular amount of coal. The response surface methodology provides a relationship among the parameters which can be utilized in finding optimal values.

5 Conclusions

In the present work, the application of response surface methodology (Box–Behnken design) for grinding of Indian coal of three different size fractions had been discussed. The three level factorial Box–Behnken experimental design model was investigated for three variables namely: grinding time, ball charge and amount of feed used for grinding of Indian coal. The three different model equations were obtained for three different size fractions of coal. MATLAB 7.1 software was used to model the equations. Predicted values of d_{80} for three different sizes were in good agreement with the experimental results in the range of R^2 value of 0.97–0.99. The model graphs were shown in 3D surface plots, contour plots as well as combination of contour and 3D surface plots were also drawn for better understanding. This study confirms that Box-Behnken design with response surface methodology can be applied for the grinding test of different size fraction of Indian coal. This technique is fast and efficient to show the final results of experiments and fewer number of experiments are required to extract the complex information of the system. Using surface response technique one can find optimum conditions for grinding of coal efficiently. This paper shows that this technique is economical as well as less time consuming.

Compliance with ethical standards

Conflict of interest We confirm that none of the authors has any competing interest related to this manuscript.

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