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Experimental studies of restoration of ball mill trunnion

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Abstract. The article deals with the analysis of experimental data on reconstruction of cement mill axles by the auxiliary machine at the place of operation. Based on the experimental research in repair the regression models of large-size equipment are developed, coefficients of equations of regression are defined. Importance of coefficients is estimated, and the adequacy of regression models is checked.

1. Introduction

In production of cementing building materials such as cement, lime and gypsum, fine grinding of raw materials is widely used. Grinding ball mills are used for grinding homogeneous materials and materials containing various corrective additives. As a result of impact of freely falling grinding bodies, which are used as balls in a rotating drum with the material under the action of centrifugal forces, grinding of raw materials takes place.

Long-term operation of mills leads to the significant wear of mainly the mechanical part of support rotating parts – axles, while losing cylindrical shape of the working surface and taking the form of a truncated cone. To restore the cylindrical surface of an axle, an additional machine [1] was developed, which allows processing at the place of operation. The selected tool is a rotary cutter, which increases the productivity of the process and the tool life [2].

Main parameters of the proposed rotary cutter are: the front angle, the angle of installation of the cutter, the angle of rotation of the cutter around the horizontal axis and the radius of the cutter cup. Experiments with the variation of the main parameters of the rotary cutter bowl will allow studying the effect of the technological parameters of the rotary cutter on the accuracy and quality of the treated surface of the restored mill axle. Definition of rational constructive and technological parameters are preferred to maximize the efficiency of the processing axle. Experiments with the variation of technological parameters of a rotary cutter are carried out.

2. Method of experiment

Experiment planning allows obtaining optimal values of output parameters with a minimum number of experiments. In the course of the experiments it is necessary to investigate the effect of technological parameters of a rotary cutter on processing the working surface of the mill axles with varying parameters. The solution of this problem makes it possible to determine the rational design and preferred technological parameters to obtain the maximum processing efficiency.

As the output parameters for determining the accuracy and the quality of the treated cylindrical surface of the mill axle with the use of an additional machine in operating conditions there is a selected area of cut layer S_s , mm² and the roughness R_a , mm.



As the main plan for the experiment, the central composite orthogonal plan of the full-factorial experiment CCOP FFE 2^4 was chosen [3]. The advantage of this plan is the simplicity of solving the calculation of the equation of estimation of variable parameters and the redundancy of the number of measurements, reducing the effect of measurement errors on the evaluation of processing parameters [4,5].

Factors characterizing the impact response functions in the process are the axle of the mill and the corresponding number of the entry conditions: universality and expressing in quantitative form selected: x_1 – front angle γ , deg.; x_2 – angle cutting bowls ω , grad.; x_3 – angle of rotation of the cutter around the horizontal axis φ , deg.; x_4 – radius of the cutting cup cutter r , mm.

The number of experiments of the central composite orthogonal plan for b factors is determined [6]:

$$N = 2^b + 2b + a_0, \quad (1)$$

where 2^b – number of star points; a_0 – number of experiments in the center of the plan.

Preparation of the planning matrix full-format experiment CCOP involves the implementation of one experiment, corresponding to the terms of the initial values of all factors; thus $a_0 = 1$. Therefore, the expression (1) takes the form:

$$N = 2^4 + 2 \cdot 4 + 1. \quad (2)$$

Thus, the number of the experiments of the experimental model of the investigated process of the axle reconstruction at 4 variable factors is $N = 25$.

3. Experimental results

The study of the influence of variable processing parameters on response functions involves the construction of a detailed planning matrix that takes into account the factors and their interaction.

Influence of factors on response functions may depend on the level at which the other factor is located, or on a combination of levels of several factors. Since it is not known a priori that there is no such dependence between the factors, we will build a detailed planning matrix that takes into account not only the factors, but also their interaction. In this case, the signs in the columns for interactions are obtained by multiplying the signs of interacting factors (table 1). Sequence of experiments is carried out by random distribution and determined by randomization to eliminate the influence of systematic errors. There are results of experimental processing of the worn axle, which has the shape of a truncated cone.

The matrix of numerical values of functions has the following property:

$$\sum_{n=1}^N x_{in} \cdot x_{jn} = 0, \quad (3)$$

where i, j – column numbers, n – number of rows of the matrix (number of experiences).

Table 1. Matrix planning CCOP PPE 2^4 and the results of the experiment

No.	x_1	x_2	x_3	x_4	Order of experiments	Varied parameters				Response function values	
						$\gamma, ^\circ$ (x1)	$\omega, ^\circ$ (x2)	$\varphi, ^\circ$ (x3)	$r, ^\circ$ (x4)	Ss mm ²	Ra, mm
1	-	-	-	-	1	23	4	15	13	0.47	3.02×10^{-3}
2	+	-	-	-	11	63	4	15	13	3.64	3.03×10^{-3}
3	-	+	-	-	24	23	26	15	13	0.58	3.11×10^{-3}
4	+	+	-	-	9	63	26	15	13	3.95	3.12×10^{-3}
5	-	-	+	-	5	23	4	61	13	2.37	4.64×10^{-3}
6	+	-	+	-	15	63	4	61	13	3.64	4.67×10^{-3}
7	-	+	+	-	18	23	26	61	13	5.34	4.72×10^{-3}
8	+	+	+	-	23	63	26	61	13	5.98	4.78×10^{-3}
9	-	-	-	+	7	23	4	15	27	1.08	0.95×10^{-3}
10	+	-	-	+	6	63	4	15	27	2.43	0.98×10^{-3}
11	-	+	-	+	20	23	26	15	27	1.22	1.02×10^{-3}
12	+	+	-	+	8	63	26	15	27	2.98	1.05×10^{-3}
13	-	-	+	+	14	23	4	61	27	1.52	2.50×10^{-3}
14	+	-	+	+	3	63	4	61	27	4.30	2.53×10^{-3}
15	-	+	+	+	10	23	26	61	27	1.71	2.58×10^{-3}

16	+	+	+	+	19	63	26	61	27	6.06	2.63×10^{-3}
17	+1.414	0	0	0	13	70	15	38	20	3.96	2.35×10^{-3}
18	-1.414	0	0	0	25	15	15	38	20	0.84	1.86×10^{-3}
19	0	+1.414	0	0	4	43	30	38	20	3.33	2.14×10^{-3}
20	0	-1.414	0	0	22	43	0	38	20	1.07	2.03×10^{-3}
21	0	0	+1.414	0	21	43	15	70	20	2.48	3.72×10^{-3}
22	0	0	-1.414	0	2	43	15	5	20	0.92	1.91×10^{-3}
23	0	0	0	+1.414	12	43	15	38	30	2.91	1.32×10^{-3}
24	0	0	0	-1.414	16	43	15	38	10	1.49	4.71×10^{-3}
25	0	0	0	0	17	43	15	38	20	1.21	2.23×10^{-3}

According to the adopted plan CCOP FFE 2^4 five levels of variation of factors are established: -1 – minimum; 0 – average; +1 – maximum; -1.414, +1.414 – “star”. Levels of variation of factors are given in table 2.

Table 2. Factors and levels of variation of independent variables of CCOP FFE 2^4

Factors studied	Coded value	Variation levels				
		-1.414	-1	0	+1	+1.414
front angle γ , deg.	x_1	15	23	43	63	70
installation angle ω , deg.	x_2	0	4	15	26	30
rotation angle φ , deg.	x_3	5	15	38	61	70
radius of cutter cutting cup r , mm	x_4	10	13	20	27	30

The analytical function regression equation, which is a mathematical model of the experimental data processing, is described by the following expression [4, 5]:

$$y = b_0 + \sum_{i=1}^n b_i x_i + \sum_{i,j=1, i \neq j}^n b_{ij} x_i x_j + \sum_{i=1}^n b_{ii} x_i^2, \quad (4)$$

where y – response function expressed in terms of coded factor values; x_i, x_j – variable factors; b_0 – free term of regression equation; b_i – coefficients of the linear dependence; b_{ij} – factors of pair interaction of factors; b_{ii} – coefficients of the quadratic dependence.

To calculate the coefficients, we use the least squares method according to the following formulas [6].

The free term of the regression equation is calculated by the formula:

$$b_0 = \frac{1}{N} \sum_{u=1}^N y_u. \quad (5)$$

Coefficients of the linear dependence are calculated on the basis of:

$$b_i = \frac{\sum_{u=1}^N x_{iu} y_u}{\sum_{u=1}^N x_{iu}^2}. \quad (6)$$

Coefficients of the pair interaction of factors are calculated by the formula:

$$b_{ij} = \frac{\sum_{u=1}^N x_{iu} x_{ju} y_u}{\sum_{u=1}^N (x_{iu} x_{ju})^2}. \quad (7)$$

Coefficients of the quadratic dependence:

$$b_{ii} = \frac{\sum_{u=1}^N x'_{iu} y_u}{\sum_{u=1}^N (x'_{iu})^2}. \quad (8)$$

The regression equation characterizing the dependence of the S_s cut-off area on the factors of variation $\gamma, \omega, \varphi, r$ in the coded form is obtained:

$$\begin{aligned} S_s = & 0.12 + 0.11x_1 + 0.06x_1^2 + 0.025x_1x_2 + 0.03x_1x_3 - \\ & -0.04x_1x_4 + 0.08x_2 + 0.05x_2^2 - 0.03x_2x_3 + 0.045x_2x_4 + \\ & + 0.055x_3 + 0.025x_3^2 + 0.011x_3x_4 - 0.05x_4 + 0.05x_4^2 \end{aligned} \quad (9)$$

The regression equation characterizing the dependence of the surface roughness R_a on the factors of variation γ , ω , φ , r in the coded form is identified:

$$R_a = 2.2 + 0.81x_1 + 0.21x_1^2 + 0.38x_1x_2 + 0.19x_1x_3 - 0.31x_1x_4 + 0.75x_2 - 0.28x_2^2 + 0.11x_2x_3 - 0.33x_2x_4 + 0.63x_3 + 0.32x_3^2 + 0.17x_3x_4 - 1.2x_4 + 0.43x_4^2. \quad (10)$$

For a detailed study of the regression models and determination of the regression equation coefficients in natural quantities, the coded values of the variable parameters x_1, x_2, x_3, x_4 should be presented as dimensional values $\gamma, \omega, \varphi, r$. Transformation, according to [7], is carried out by the formula:

$$x_j = \frac{X_j - X_{j0}}{\Delta X_j} \quad (11)$$

where x_j – coded value of the j -th input factor; X_j – natural value of the input factor; X_{j0} – natural value of the average level of the input factor; ΔX_j – variation interval of the j -th input factor.

According to (11), the coded values of the coefficients x_1, x_2, x_3, x_4 for the natural values are obtained:

$$\begin{cases} x_1 = \frac{\gamma - 43}{20} \\ x_2 = \frac{\omega - 15}{11} \\ x_3 = \frac{\varphi - 38}{13} \\ x_4 = \frac{r - 20}{7} \end{cases} \quad (12)$$

The significance of the regression equation parameters is estimated by the method of statistical testing of hypotheses – the Student's criterion. Insignificant coefficients are equal to zero; the remaining coefficients can not be recalculated due to the orthogonality of the plan [8].

By converting the expression (9) according to (12), we obtain a regression equation for the cut area S_s , describing the processing of the axle, having the shape of a truncated cone, in natural values:

$$S_{cp} = 0.088 + 0.05\gamma - 0.011\omega - 0.049\varphi - 0.032r + 0.00015\gamma^2 + 0.00041\omega^2 + 0.00015\varphi^2 + 0.00102r^2 - 0.000113\gamma\omega + 0.000115\gamma\varphi - 0.000286\gamma r - 0.00021\omega\varphi + 0.00058\omega - 0.00012\varphi r. \quad (13)$$

The significance of the parameters for the regression equation of the cut area is determined using the coefficient of elasticity, showing the degree of quantitative change of one factor relative to another:

$$E_i = \frac{a_i \cdot x_{i0}}{a_0} \quad (14)$$

where x_{i0} – natural value of the average level of the input factor; a_0, a_i – coefficients of the regression equation.

The significance of the parameters is determine by the formula:

$$\xi = \frac{E_i}{E_\Sigma} \cdot 100\%. \quad (15)$$

Values for the area of the slice S_s :

$$\begin{aligned} a_0 &= 0.088; a_1 = 0.05; a_2 = 0.011; a_3 = 0.049; a_4 = 0.032; \\ E_1 &= 24.4; E_2 = 1.88; E_3 = 21.16; E_4 = 7.27; \\ \xi_1 &= 44.6\%; \xi_2 = 3.4\%; \xi_3 = 38.7\%; \xi_4 = 13.3\%. \end{aligned}$$

The results are presented in the form of a diagram in Figure 1.

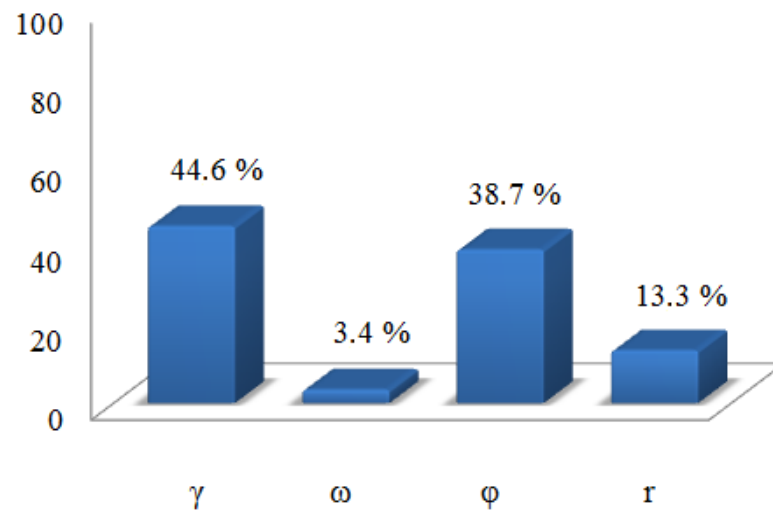


Figure 1. Diagram of the importance of parameters for the cut area.

The analysis of the chart shows that the most significant impact of the indicator on the area of the cut is the front angle γ (44.6 %) and the angle of rotation φ (38.7 %). The radius of the cutting cup r has little effect (13.3 %), however, it partially affects the size of the cut area. The influence of the setting angle of the cutter ω is minimal (3.4 %).

The above can be explained by the fact that increasing the front angle and the angle of rotation reduces the deformation of the cut layer, cutting force and power consumed. Increasing the quality of the surface, and the chip exit conditions are improved. However, the excessive increase weakens the cutting blade, increases its wear due to chipping and deterioration of the heat sink.

By transforming the expression (10) according to (12), we obtain the regression equation for the surface roughness R_a , describing the treatment of the axle, having the form of a truncated cone, in natural quantities:

$$\begin{aligned}
 R_a = & 9.34 - 0.014\gamma - 0.019\omega - 0.176\varphi - 0.434r + \\
 & + 0.000525\gamma^2 + 0.00231\omega^2 + 0.00189\varphi^2 + 0.00878r^2 + \\
 & + 0.001727\gamma\omega + 0.000731\gamma\varphi - 0.002214\gamma r + \\
 & + 0.000769\omega\varphi - 0.004285\omega r + 0.001868\varphi r.
 \end{aligned} \tag{16}$$

Let us determine the significance of the factors for roughness:

$$\begin{aligned}
 a_0 = & 9.34; a_1 = 0.014; a_2 = 0.019; a_3 = 0.176; a_4 = 0.434; \\
 E_1 = & 0.06; E_2 = 0.03; E_3 = 0.72; E_4 = 0.93; \\
 \xi_1 = & 3.4\%; \xi_2 = 1.7\%; \xi_3 = 41.4\%; \xi_4 = 53.5\%.
 \end{aligned}$$

Results are presented in a diagram in Figure 2. In this case, the rotation angle φ (41.4 %) and the radius of the cutting cup r (53.5%) have a significant effect. In comparison with the considered influence of variable factors on the cut area, the influence of the front angle γ decreased tenfold to 3.4% and the influence of the cutter angle ω (1.7%) decreased 2 times.

The obtained values of the effect are explained by the fact that the increase in the radius of rounding of the tip of the cutter reduces the height of irregularities – R_a roughness, with an increase in the angle of rotation of the axis decreasing the chip descent, which also has a positive effect on the quality of the treated surface.

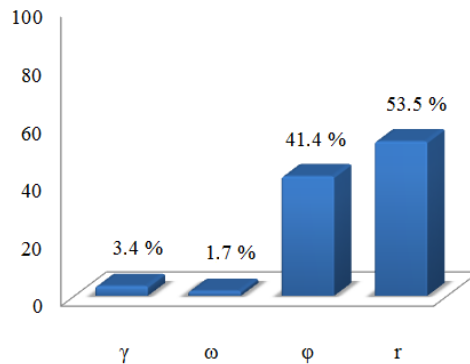


Figure 2. Diagram of the importance of parameters for roughness.

After calculating the coefficients to check the suitability of the model, the adequacy of the regression equation is checked. It is necessary to calculate the variance of the adequacy of the (S_{ad}) variance of the repeatability of experience (S_y) (Table 3) [9].

Table 3. Calculation of the dispersion function

No	Variable factors				Response function and variance function values			
	γ	ω	ϕ	r	S_s, mm^2	$(S_s - \bar{S}_s)^2$	R_a, mm	$(R_a - \bar{R}_a)^2$
1	23	4	15	13	0.47	4.61906064	3.02×10^{-3}	0.099856×10^{-3}
2	63	4	15	13	3.64	1.04203264	3.03×10^{-3}	0.106276×10^{-3}
3	23	26	15	13	0.58	4.15833664	3.11×10^{-3}	0.164836×10^{-3}
4	63	26	15	13	3.95	1.77102864	3.12×10^{-3}	0.173056×10^{-3}
5	23	4	61	13	2.37	0.06210064	4.64×10^{-3}	3.748096×10^{-3}
6	63	4	61	13	3.64	1.04203264	4.67×10^{-3}	3.865156×10^{-3}
7	23	26	61	13	5.34	7.40275264	4.72×10^{-3}	4.064256×10^{-3}
8	63	26	61	13	5.98	1.29497664	4.78×10^{-3}	4.309776×10^{-3}
9	23	4	15	27	1.08	2.36913664	0.95×10^{-3}	3.076516×10^{-3}
10	63	4	15	27	2.43	0.03579664	0.98×10^{-3}	2.972176×10^{-3}
11	23	26	15	27	1.22	1.95776064	1.02×10^{-3}	2.835856×10^{-3}
12	63	26	15	27	2.98	0.13017664	1.05×10^{-3}	2.735716×10^{-3}
13	23	4	61	27	1.52	1.20824064	2.50×10^{-3}	0.041616×10^{-3}
14	63	4	61	27	4.30	2.82508864	2.53×10^{-3}	0.030276×10^{-3}
15	23	26	61	27	1.71	0.82664464	2.58×10^{-3}	0.015376×10^{-3}
16	63	26	61	27	6.06	11.83910464	2.63×10^{-3}	0.005476×10^{-3}
17	70	15	38	20	3.96	1.79774464	2.35×10^{-3}	0.125316×10^{-3}
18	15	15	38	20	0.84	3.16555264	1.86×10^{-3}	0.712336×10^{-3}
19	43	30	38	20	3.33	0.50523664	2.14×10^{-3}	0.318096×10^{-3}
20	43	0	38	20	1.07	2.40002064	2.03×10^{-3}	0.454276×10^{-3}
21	43	15	70	20	2.48	0.01937664	3.72×10^{-3}	1.032256×10^{-3}
22	43	15	5	20	0.92	2.88728064	1.91×10^{-3}	0.630436×10^{-3}
23	43	15	38	30	2.91	0.08456464	1.32×10^{-3}	1.915456×10^{-3}
24	43	15	38	10	1.49	1.27509264	4.71×10^{-3}	4.024036×10^{-3}
25	43	15	38	20	1.21	1.98584464	2.23×10^{-3}	0.224676×10^{-3}

$$\bar{S}_s = 2.6192 \quad \sum_{i=1}^{25} (S_s - \bar{S}_s)^2 = 66.704984 \quad \bar{R}_a = 2.704 \times 10^{-3} \quad \sum_{i=1}^{25} (R_a - \bar{R}_a)^2 = 37.6812 \times 10^{-3}$$

Calculating the variance of reproducibility of the experiment, we use the formula [10]:

$$S^2(y) = \frac{1}{n-1} \sum_{i=1}^N (y - \bar{y})^2. \quad (17)$$

Hence, the variance of function reproducibility:

$$S^2(S_s) = 2.779374; \quad S^2(R_a) = 1.57005 \times 10^{-3}.$$

To find the residual variance or adequacy variance, we use the formula [11]:

$$S_{ad}^2 = \frac{\sum_{i=1}^N \Delta y_i^2}{f}, \quad (18)$$

where Δy_i^2 – residual sum of squares (table 3); f – number of degrees of freedom, which is the difference between the number of experiments and the number of coefficients.

Variance of adequacy of regression models:

$$S_{ad}^2(S_{cp}) = 6.6704984; \quad S_{ad}^2(R_a) = 3.76812$$

To test the hypothesis of the adequacy of the model, we use the Fisher's criterion, which is determined by the formula:

$$F = \frac{S_{ad}^2}{S^2(y)}. \quad (19)$$

From here we find the calculated value of the Fisher criterion for the regression model: $F(S_s, R_a) = 2.4$; comparing it with a table value at a 5% significance level $F_{table} = 2.78$ [7], we receive:

$$F_{calc} < F_{table}. \quad (20)$$

Since the calculated value of the Fisher test does not exceed the table, with a confidence probability of 5%, the model can be considered adequate.

4. Conclusion

1. Based on the experimental study, the correlation regression equations are obtained, which show dependence of the cut layer area and the surface roughness of mill axles on the studied factors: the front angle, the rotation angle, the installation angle and the radius of the cutting bowl.

2. Estimation of the significance of regression model parameters was according to the Student's criterion, the results of which determined significant influence of the front angle and the angle of rotation of the rotary cutter on the size of the cut area, and the radius of a cutting bowl with the angle of rotation of a cutter on roughness.

3. The adequacy of the regression model was checked by the Fisher's criterion with a 5% confidence probability.

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