Optimization of Internal Cylindrical Grinding Process Parameters for SAE 52100 Steel using Taguchi Method

Mr. S.R.Shaikh[1], Prof. G.D.Shelake[2], Mr. R.D.Deshmukh[3], Prof. S.N.Dhole[4], Prof. Mohmmad Irfan[5]

[1]ME-Student, Dept. of Mechanical Engineering, MSS's College of Engineering & Tech., Jalna, Maharashtra, India
[2]Asst.Professor, Dept. of Mechanical Engineering, MSS's College of Engineering & Tech., Jalna, Maharashtra, India
[3]Sr. Manager (Manufacturing), NRB Bearings ltd., Jalna, Maharashtra, India
[4]Asst. Professor, Dept. of Mechanical Engineering, MSS's College of Engineering & Tech., Jalna, Maharashtra, India
[5]Asst. Professor, Dept. of Mechanical Engineering, MSS's College of Engineering & Tech., Jalna, Maharashtra, India

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Abstract - *In precision grinding operations, it is often important to set the correct grinding machine parameters so as to produce parts of required quality. In order to decrease the cost and increase the production rate, the grinding machine must be set to operate within the shortest possible grinding cycle time. In this study a series of experiments are performed on hardened steel SAE 52100 (62 HRC) with an aluminum oxide (Al_2O_3) grinding wheel. The selected input parameters are wheel speed (V_{wheel}),work speed (V_{work}), feed rate(f) and output parameters are surface roughness (R_a), cycle time (C_t). The main objective of this study is to find out the optimal combination of internal cylindrical grinding process parameters by using Taguchi's design of experiments (DOE) method.*

Key Words: Grinding, Surface roughness (R_a), Cycle time (C_t), SAE 52100, Al_2O_3, DOE.

1. INTRODUCTION

In today's rapidly changing scenario in manufacturing industries, applications of optimization techniques in metal cutting processes is essential for a manufacturing unit to respond effectively to severe competitiveness and increasing demand of quality product in the market. It is required to systematically investigate the process or product variables in order to enhance the product's manufacturability, reliability and quality [3]. Most of the researchers have investigated the influence of cylindrical grinding parameters like wheel characteristics, workpiece characteristics, machine characteristics, process characteristics etc. [4-10]. Limited work has been reported on the modeling and analysis of effects of process parameters on the performance characteristics of internal cylindrical grinding process. In this study, the efforts are applied to improve the surface roughness and cycle time of internal cylindrical grinding by setting the process parameters at optimum level with the help of Taguchi's Design of Experiment (DOE) method.

1.2 Objectives

1. To investigate the effect of input parameters that minimizes surface roughness and its analysis.
2. To investigate the effect of input parameters that minimizes cycle time and its analysis.
3. To obtain regression equation for surface roughness and cycle time.
4. To optimize the parameter levels for minimization of surface roughness and cycle time.
5. To validate the developed model by confirmation experiment and comparing it with mathematical predicted values

2. EXPERIMENTAL SETUP

2.1 Work Material

In this study, SAE 52100 steel was selected as the work piece material. Initially it is available as seamless tube of specifications i.e., outer diameter 42.80 mm and inner diameter 29.65 mm respectively. It undergoes different processes and then available in the form of inner ring (Ø 29.70 mm bore) of cylindrical roller bearing (NUP 2206 EG15) for internal cylindrical grinding. After performing internal cylindrical grinding operation its bore size is maintained at Ø 30 mm.

Table 2.1: Chemical properties of SAE 52100 steel

C 1.02%	Si 0.21%	S 0.003%	P 0.01%	Mn 0.38%
Ni 0.06%	Cr 1.42%	Mo 0.02%	Cu 0.13%	Sn 0.006%
Al 0.024%	Ti 0.0018%	V 0.0002%	Ca 0.0002%	

Table 2.2: Mechanical properties of SAE 52100 steel

Hardness	62 HRC
Bulk modulus (K)	140 GPa
Shear modulus (G)	80 GPa
Elastic modulus (Y)	190-210 GPa
Poisson's ratio (M)	0.27-0.30

2.2 Tool Material

In this study, Aluminium oxide (Al_2O_3) was selected as tool material. The tool used for internal cylindrical grinding process is of specifications 20x24x8 (mm) in size and grinding wheel coding specifications as PA120 M8 V30.

2.3 Experimental machine setup

Figure 2.1: CIMAT 1F-CE CNC machine

The experiments are performed on CIMAT 1F-CE internal cylindrical grinding machine shown in figure 2.1. The CIMAT 1F-CE is a CNC universal internal cylindrical grinding machine for the individual and batch production of short to long-sized workpieces. It has a distance between centers of 400mm and a center height of 175mm. It can machine workpieces with a maximum weight of 5kg. The technical specifications of CIMAT 1F-CE internal cylindrical grinding machine is as shown in table2.3.

Table 2.3: Technical specifications of CIMAT 1F-CE machine

SR. NO.	PARAMETER	SPECIFICATION
1	Make	CIMAT
2	Model	2GR 6082
3	Type	CNC
4	Min. Grinding	10 mm
5	Max. Grinding	65 mm
6	Max. Grinding length	40 mm
7	Main motor power	25 Kw
8	Mains connection	380V / 50 Hz
9	Machine weight	3700 kg

2.4 Taguchi's DOE method

Dr. Taguchi's standardized version of DOE, popularly known as the Taguchi method or Taguchi approach, was introduced in the USA in the early 1980's. Now-a days it is the most effective quality building tool used by engineers for all fields of manufacturing activity. The DOE using Taguchi approach can economically satisfy the needs of problem solving and product/process design optimization projects. Dr. Genechi Taguchi is regarded as the foremost proponent of robust parameter design, which is an engineering method for product or process design that focuses on minimizing variation and/or sensitivity to noise. When used properly, Taguchi designs provide a powerful and efficient method for designing products that operate consistently and optimally over a variety of conditions [3].

Taguchi's method is employed with the following steps to optimize the input parameters so that the performance of the process is improved:

1. Identify the factors/interactions
2. Identify the levels of each factor
3. Select an appropriate orthogonal array (OA)
4. Assign the factors/interactions to columns of OA
5. Conduct the experiments
6. Analyze the data & determine the optimal levels
7. Conduct the confirmation Experiment

3. RESULT AND DISCUSSION

3.1 Experimental Results for Surface Roughness and Cycle Time

The experimental results for surface roughness and cycle time are listed in table 3.2. The results are obtained with respect to the experimental runs which are the combinations of set of parameters designed by Taguchi's design of experiment (DOE) method. The 9 runs of experiment are carried out for low level, medium level and high level parameters. The analysis of results is done by analyzing Taguchi design. Analysis of variance (ANOVA) table, estimated effects and coefficients table and main effects plot, normal plot of standardized effect are drawn for surface roughness and cycle time each point separately. Also mathematical model for surface roughness and cycle time are obtained by using the coefficients of each parameter. Then optimum set of parameters is obtained using D-optimal method of optimization.

3.1.1 Selection of Parameters and Levels

Table 3.1 represents process parameters along with their various levels used in experimentation. Parameter ranges are decided on the basis of Literature review recommended and machine feasibility and specifications given by bearings manufacturer.

Table 3.1: Process parameters and levels

PARAMETER	LEVEL 1	LEVEL 2	LEVEL 3
WHEEL SPEED	25000	29000	33000
WORK SPEED	800	1000	1200
FEED RATE	0.3	0.75	1.2

3.1.2 Experimentation

The present investigation work is carried out for 3 factors (wheel speed, work speed and feed rate), each factor at 3 levels. Therefore L9 (3^3) orthogonal array according to Taguchi's method is chosen for conducting the experiments.

Table- 3.2 The experimental results for surface roughness and cycle time

Expt. No.	Wheel speed (V_{wheel}) Rpm	Work speed (V_{work}) rpm	Feed rate (f) mm/min	Surface roughness (R_a) µm	Cycle time (C_t) Sec
1	25000	800	0.3	0.32	30
2	25000	1000	0.75	0.36	33
3	25000	1200	1.2	0.34	27
4	29000	800	0.75	0.31	28
5	29000	1000	1.2	0.35	33
6	29000	1200	0.3	0.40	30
7	33000	800	1.2	0.29	29
8	33000	1000	0.3	0.26	34
9	33000	1200	0.75	0.27	32

3.2 Analysis for Surface Roughness using Taguchi Method

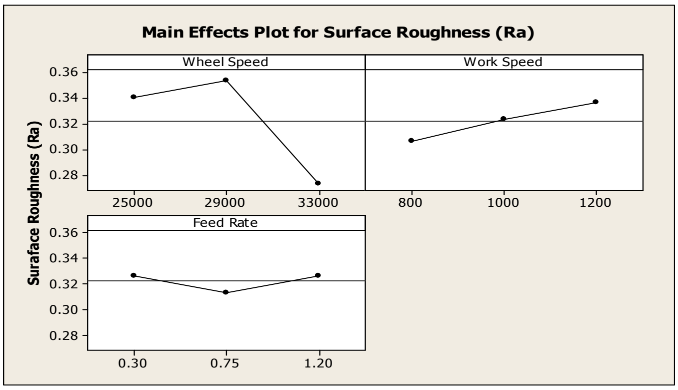
The analysis of surface roughness is carried out using Taguchi method in which the influences of each input parameters on surface roughness are obtained and which are listed in table 3.3. Also estimated effect and coefficient are obtained, by using these coefficients regression equation is obtained for surface roughness. Also parameter influence is plotted on main effects plot for each parameter and normal plot of the standardized effect.

3.2.1 Parameters Influence on Surface Roughness

Table 3.3 shows that analysis of variance (ANOVA) results for surface roughness. The table shows F-distribution and p-values for each factor. The p-value for all the input parameters such as wheel speed (V_{Wheel}), work speed (V_{Work}) and feed rate (f) are 0.025, 0.045 and 0.006 respectively, which indicates that all input parameters shows more significant effect on responses.

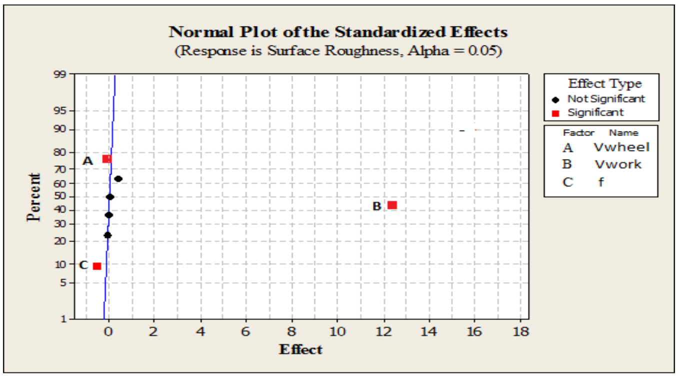
Table 3.3: Analysis of Variance (ANOVA) for Surface Roughness

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Wheel Speed	2	0.3818	0.3818	0.1909	0.69	0.025
Work Speed	2	2.5673	2.5673	1.2836	4.67	0.045
Feed Rate	2	0.4019	0.4019	0.2009	0.73	0.006
Residual Error	2	0.5500	0.5500	0.2750	-	-
Total	8	3.9009	-	-	-	-



Graph 3.1: Main Effects plot Surface Roughness (R_a)

Graph 3.1 shows the main effect plots for surface roughness which indicates the variation of surface roughness with respect to each input parameter.

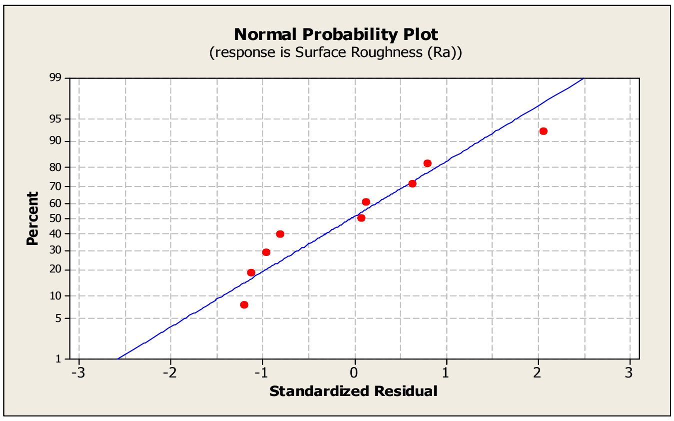


Graph 3.2: Normal Plot for Standardized Effect

Graph 3.2 shows normal plot indicates the percent effect of each parameter on surface roughness, there are three significant effects ($\alpha \leq 0.05$). These significant effects includes all three main effects, wheel speed (V_{Wheel}), work speed (V_{Work}) and feed rate (f). In which, wheel speed (V_{Wheel}) shows 78.64% effect, work speed (V_{Work}) shows 41.23% effect and feed rate (f) shows 9.75 % effect.

The regression equation for surface roughness is as follows.

Surface Roughness (Ra) = 0.4889 - 0.000084 V_{Wheel} + 0.000075V_{Work} - 0.00020 f



Graph 3.3: Normal Probability Plot

The model listed above can be used to predict the surface roughness, and Graph 3.3 display the normal probability plots of the residuals for surface roughness. It notices that the residual generally falling on straight line, which means error are normally distributed. Further it indicates that the developed regression mathematical model can yield very accurate results.

3.3 Analysis for Cycle Time Using Taguchi Method

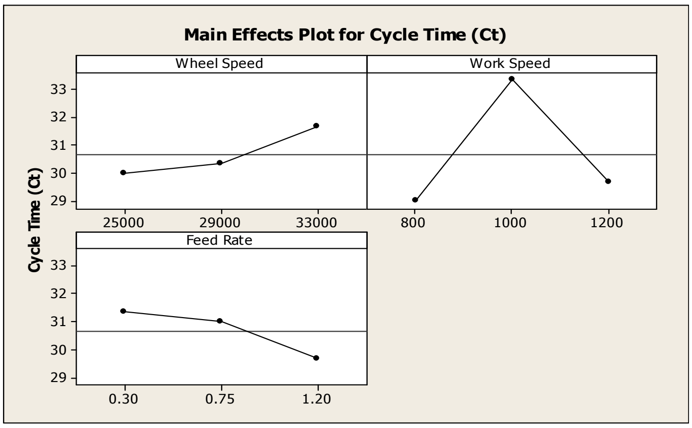
The analysis of cycle time is carried out using Taguchi method in which the influences of each input parameters on cycle time are obtained and which are listed in table 3.4. Also estimated effect and coefficient are obtained by using these coefficients regression equation is obtained for cycle time. Also parameter influence is plotted on main effects plot for each parameter and normal plot of the standardized effect.

3.3.1 Parameters Influence on Cycle Time

The analysis of variance (ANOVA) results for cycle time. The p-value for all the input parameters such as wheel speed (V_{Wheel}), work speed (V_{Work}) and feed rate (f) are 0.043, 0.033 and 0.005 respectively, which indicates that all input parameters shows more significant effect on cycle time.

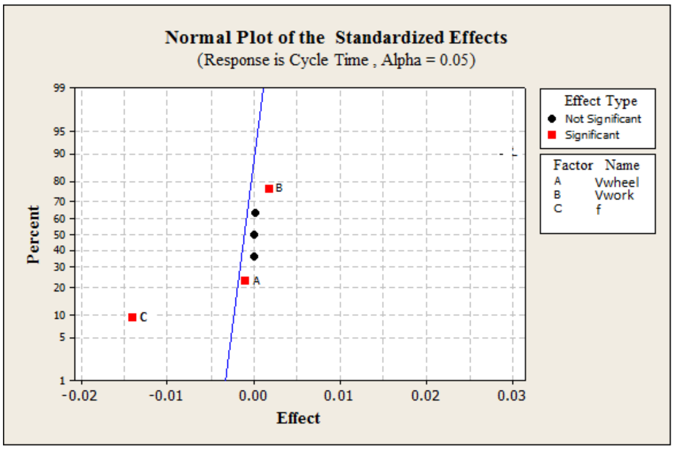
Table 3.4: Analysis of Variance (ANOVA) for CycleTime

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Wheel Speed	2	2.552	2.552	1.276	0.86	0.043
Work Speed	2	16.291	16.291	8.145	5.48	0.033
Feed Rate	2	2.347	2.347	1.173	0.79	0.005
Residual Error	2	2.972	2.972	1.486	-	-
Total	8	24.162	-	-	-	-



Graph 3.4: Main Effects Plot for Cycle Time

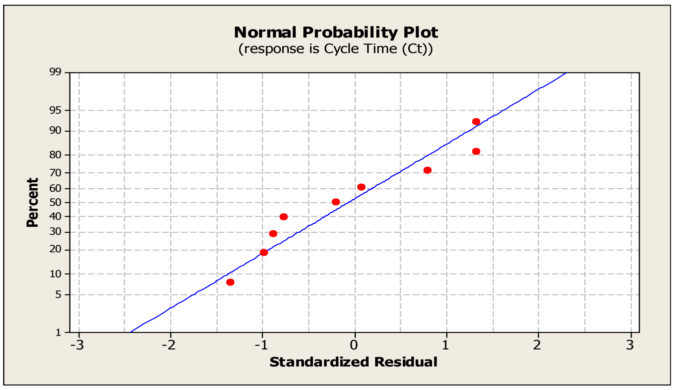
Graph 3.4 shows the main effect plots for cycle time which indicates the variation of cycle time with respect to each input parameter.



Graph 3.5: Normal Plot of Standardized Effects

Graph 3.5 shows normal plot indicates the percent effect of each parameter on cycle time, there are three significant effects ($\alpha \leq 0.05$). These significant effects includes all three main effects, wheel speed (V_{Wheel}), work speed (V_{Work}) and feed rate (f). In which wheel speed (V_{Wheel}), shows 22.86% effect, work speed (V_{Work}) shows 78.75% effect, feed rate (f) shows 9.97% effect.

The regression equation for cycle time is as follows.
Cycle Time (Ct) = 24.3 + 0.000208 V_{Wheel} + 0.00167 V_{Work} - 1.85 f



Graph 3.6: Normal Probability Plot

The model listed above can be used to predict the cycle time and Graph 3.6 display the normal probability plot of the residuals for cycle time. It notices that the residual generally falling on straight line, which means error are normally distributed. Further it indicates that the developed regression mathematical model can yield very accurate results.

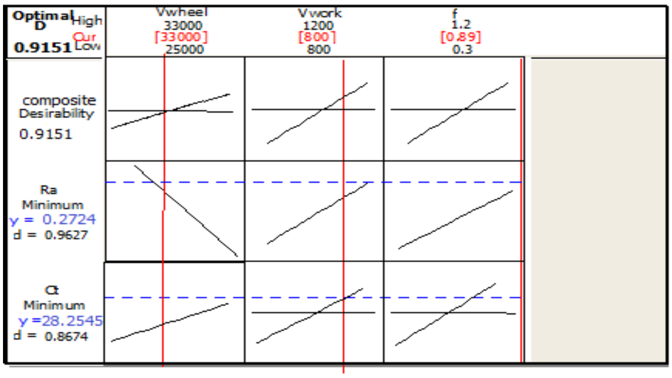
3.4 Response Optimization

Table 3.5 shows input data for optimization which is used to determine optimum set of parameters. The optimization is carried out by using 'D' optimal method of optimization with the help of Minitab17 software.

Table 3.5: Input Data for Response Optimization

Responses	Goal	Lower Value	Upper Value	Weight	Import
Surface Roughness	Minimize	0.26	0.40	1	1
Cycle Time	Minimize	27	34	1	1

Graph 3.7 shows the response optimization plot. Parameters levels with red colour indicate the optimum level of parameters for optimum responses. From the response optimization plot it is clear that, wheel speed (V_{Wheel}) should be 33000 rpm; it means that optimum value for wheel speed should be at higher level. The work speed (V_{Work}) should be 800 rpm; it means that optimum value for work speed should be at low level. The feed rate should be 0.89 mm/min; it means that optimum value for feed rate 74.17%. The composite desirability of response optimization plot is 0.9151.



Graph 3.7: Response Optimization Plot

Table 3.6: Optimization Set of Parameters (Actual)

Parameters	Optimum Value (Actual)
Wheel Speed (V_{Wheel})	33000 rpm
Work Speed (V_{Wheel})	800 rpm
Feed Rate (f)	0.89 mm/min

3.5 Confirmation Experiments

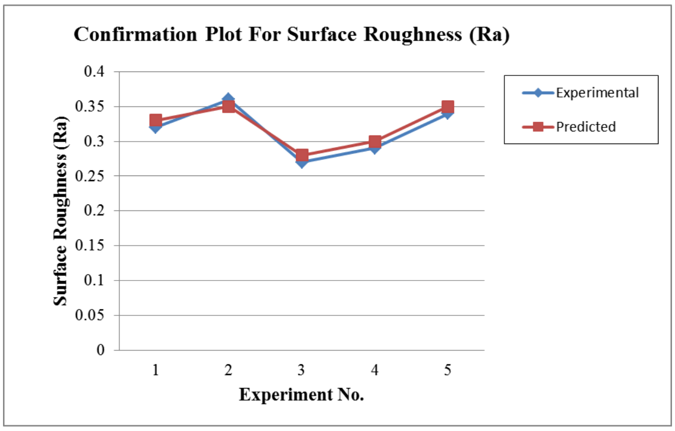
The five confirmation run experiments are performed for surface roughness (R_a) and cycle time (C_t) are listed in table 3.7 and table 3.8 respectively. The mean absolute error between the experimental and predicted value is found to be 3.13 and 3.25 for surface roughness (Ra) and cycle time (Ct) respectively.

Table 3.7: Confirmation Experiment for Surface Roughness and Comparison with Predicted Results

Expt. No.	Input Parameters			Surface Roughness (Ra)		
	V_{wheel}	V_{Work}	f	Experimental	Predicted	% Error
1	29000	1000	0.75	0.32	0.33	3.03
2	29000	1200	0.3	0.36	0.35	2.86
3	33000	800	0.75	0.27	0.28	3.57
4	33000	1000	1.2	0.29	0.3	3.33
5	29000	1200	1.2	0.34	0.35	2.86
Mean Absolute Error						**3.13**

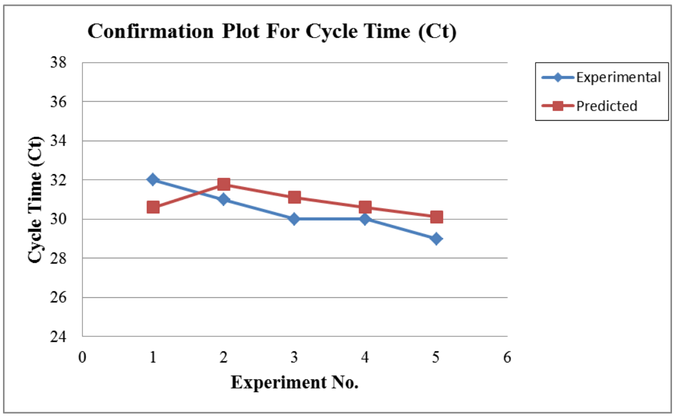
Table 3.8: Confirmation Experiment for Cycle Time and Comparison with Predicted Results

Expt. No.	Input Parameters			Cycle Time (Ct)		
	V_{wheel}	V_{work}	f	Experimental	Predicted	% Error
1	29000	1000	0.75	32	30.61	4.54
2	29000	1200	0.3	31	31.78	2.45
3	33000	800	0.75	30	31.11	3.57
4	33000	1000	1.2	30	30.61	1.99
5	29000	1200	1.2	29	30.12	3.72
Mean Absolute Error						**3.25**



Graph 3.7: Confirmation Plot for Surface Roughness (Ra)

Graph 3.7 shows comparison of experimental and predicted values of surface roughness. It indicates that there is good agreement between experimental and predicted results obtained from regression model and it is within acceptable range. Hence this confirms excellent reproducibility of the experimental conclusions.



Graph 3.8: Confirmation Plot for Cycle Time (Ct)

Graph 3.8 shows comparison of experimental and predicted values of cycle time. It indicates that there is good agreement between experimental and predicted results obtained from regression model and it is within acceptable range. Hence this confirms excellent reproducibility of the experimental conclusions.

4. CONCLUSIONS

The following conclusions are drawn based on experimental results for effective response.

1. Surface Roughness Investigation: The values of input parameters such as higher value of wheel speed (V_{Wheel} = 33000 rpm), medium value of work speed (V_{Work} = 1000 rpm) and lower value of feed rate (f = 0.30 mm/min) provides the minimum value of surface roughness which is equals to 0.26 µm.

2. CycleTime Investigation: The values of input parameters such as lower value of wheel speed (V_{Wheel} = 25000 rpm), higher value of work speed (V_{Work} = 1200 rpm) and higher value of feed rate (f = 1.20 mm/min) provides the minimum value of cycle time which is equals to 27 sec.

3. Regression Equation: The following mathematical models are obtained for surface roughness and cycle time from regression results.

Surface Roughness (Ra) = $0.4889 - 0.000084\ V_{Wheel} + 0.000075 V_{Work} - 0.00020\ f$

Cycle Time (Ct) = $24.3 + 0.000208\ V_{Wheel} + 0.001667\ V_{Work} - 1.85\ f$

4. Response Optimization: It is observed that minimum surface roughness (R_a=0.26 µm) and cycle time (C_t=27 sec) are obtained simultaneously by employing V_{Wheel} = 33000 rpm, V_{Work} = 800 rpm and f = 0.89 mm/min.

5. **Validation of Experimental Results:** The mean absolute error between the experimental and predicted value is found to be 3.13 and 3.25 for the surface roughness and cycle time respectively. The prediction made by Regression Analysis is in good agreement with Confirmation results.

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BIOGRAPHIES

Mr. Shakil R. Shaikh
ME-Student
(MSS's CET, Jalna, Maharashtra)

Prof. G. D. Shelake
Asst. Professor
(MSS's CET, Jalna, Maharashtra)

Mr. R. D. Deshmukh
Sr. Manager
(NRB Bearings Ltd., Jalna, Maharashtra)

Prof. S. N. Dhole
Asst. Professor
(MSS's CET, Jalna, Maharashtra)

Prof. Mohmmad. Irfan
Asst. Professor
(MSS's CET, Jalna, Maharashtra)