Proceedings of the
International Conference on Mechanical Engineering 2009
(ICME2009) 26- 28 December 2009, Dhaka, Bangladesh

ICME09-RT-20

MULTI-OBJECTIVE OPTIMIZATION OF CUTTING PARAMETERS FOR SURFACE ROUGHNESS IN CYLINDRICAL GRINDING USING RESPONSE SURFACE METHOD

B. C.Routara[1], P. Sahoo[2] and A. Bandyopadhyay[2]

[1] Department of Mechanical Engineering, KIIT University, Bhubaneswar
[2] Department of Mechanical Engineering, Jadavpur University, Kolkata.

ABSTRACT

In the present research, response surface methodology (RSM) has been applied to determine the optimum cutting conditions leading to minimum surface roughness in cylindrical grinding operation on AISI 1040 mild steel. The second order mathematical models in terms of machining parameters were developed for surface roughness prediction using RSM on the basis of experimental results. The model selected for optimization has been validated with F-test. The adequacy of the models on surface roughness has been established with Analysis of Variance (ANOVA). An attempt has also been made to optimize cutting parameters using multi-objective characteristics for the surface roughness prediction models.

Keywords: Cylindrical Grinding, Optimization, Surface Roughness, ANOVA.

1. INTRODUCTION

Surface finish is an important attribute of quality in any machining operation. The accuracy of mating surface is directly proportional to the surface finish produced on the machined part. Good surface finish, especially in grinding contributes to the aesthetic appeal of the product. Grinding is a complex machining process with a lot of interactive parameters, which depend upon the grinding type and requirements of products. However, surface quality produced in grinding is influenced by the following parameters.

(i) Workpiece: Mechanical properties, chemical composition and fracture mode etc.
(ii) Wheel: Abrasives, grain size, grade, structure, binding material, shape and size etc.
(iii) Process: Wheel speed, workpiece speed, longitudinal feed (feed rate), radial infeed (depth of cut) and dressing conditions etc.
(iv) Machine: static and dynamic characteristics, spindle system, and table system etc.

It is very difficult to consider all these parameters that control the surface roughness. In grinding operation, it is essential to select the process parameters to achieve the high quality performance. A lot of attempts have been made to study the grinding process effectively to evaluate the factors affecting surface roughness in cylindrical grinding. Kwak [1] investigated the various grinding parameters that affected the geometric error in surface grinding process using combined Taguchi method and RSM. Kwak *et al*. [2] analyzed the surface roughness of the product and grinding power spent during the process in the external cylindrical grinding of hardened SCM440 steel using RSM. The findings of this research work are that the depth cut is more influential factor than the traverse speed for the grinding power and an increase in infeed changes the maximum height of the surface roughness more than the centre line average height. Shaji and Radhakrishnan [3] presented a study on Taguchi method to evaluate the process parameters in surface grinding with graphite as lubricant. The effect of process parameters such as speed, feed, infeed and modes of dressing are analyzed. Dhavlikar *et al.* [4] reported that the Taguchi and dual response method can be used effectively to determine robust condition for minimization of roundness error of workpiece for centerless grinding operation. Hecker and Liang [5] put a thought on prediction of the R_a based on a probabilistic undeformed chip thickness model. In this model, surface roughness is expressed as the function of wheel microstructure, the process kinematic conditions, and the material properties. A simple expression has been derived to correlate the surface roughness with the chip thickness. Zhong *et al.* [6] characterize the surface finish of thermally sprayed and precision machined WC-Co and alloy-625 coating on the grinding operation. They characterized the scaling behavior of the surfaces using various cut-off lengths, sampling lengths, numbers of sampling and cut-off lengths for measuring the surface roughness parameters R_a and R_q (root mean square roughness value). The surface roughness heights of the machined surfaces were found to be dependent on the scale of cut-off length as a power law. Sun *et al.* [7] investigated that the level of surface roughness and depth of sub-surface damage vary differently for different grinding modes. Atzeni and Iuliano [8] developed mathematical model for R_a and kinematic parameters using regression analysis. The developed model shows that the roughness is mainly influenced by the feed per grain and cutting speed. A smoother surface is produced by decreasing the feed per grain, though the spacing between successive peaks along the workpiece and depth of engagement decreases. Choi *et al.* [9] established the generalized model for power, surface roughness, grinding ratio and surface burning for various steel alloys and alumina grinding wheels. It has been shown that these models can predict process conditions over a wide range of grinding conditions. Liu *et al.* [10] designed a force control system in a CNC grinding machine to reduce the grinding force variation and surface roughness. They conducted series of experiments using Taguchi method. The experimental result showed that surface roughness decreased with a slower feed rate and also with larger grinding force. Review of available literature shows that R_a has been the focus of most of the studies. The present study aims at consideration of five different roughness parameters, namely centre line average roughness (R_a), root mean square roughness (R_q), skewness (R_{sk}), kurtosis (R_{ku}) and mean line peak spacing (R_{sm}) for the surface texture generated in grinding operation.

2. RESPONSE SURFACE METHOD

Response surface method (RSM) adopts both mathematical and statistical techniques which are useful for the modelling and analysis of problems in which a response of interest is influenced by several variables. RSM attempts to analyze the influence of the independent variables on a specific dependent variable (response). The mathematical model commonly used for the machining response Y is represented as

$$Y = \psi(d, N, f) + \varepsilon \qquad (1)$$

where, d, N, f are depth of cut, spindle speed and feed rate respectively and ε is the error which is normally distributed about the observed machining response *Y*. Let $\psi(d, N, f) = \eta$ .The surface represented by 'η' is called response surface.

Second order polynomial Model (Quadratic model**)**

$$Y_u = b_0 + \sum_{i=1}^{n} b_i x_{iu} + \sum_{i<j}^{n} b_{ij} x_{iu} x_{ju} + \sum_{i=1}^{n} b_{ii} x_{iu}^2 \qquad (2)$$

where $Y_u = f\,(Y - \varepsilon)$, is proposed expected response on higher-order polynomial and x_is are process variables such as depth of cut ,spindle speed and feed rate respectively, and *b*' s are regression coefficients can be calculated by linear multiple regression analysis.

3. DESIGN OF EXPERIMENTS

The design of experiments is a very powerful tool, which permits us to carry out the modeling and analysis of the influence of process variables on the response variables. For the present work the factors considered for experimentation are workpiece speed (*N*) in rpm, longitudinal feed (*f*) in mm/rev and radial infeed (*d*) in mm. Other parameters were assumed to be constant over the experimental domain. Machining has been carried out by varying one of the process parameters while keeping the rest at constant values.

Based on 4^3 factorial design, the selected design matrix constitute a four level three factor full factorial design consisting of 64 sets of coded conditions. The process variables with their units, notations and values on different levels are listed in the Table.1. The selection of the values of the variables is limited by the capacity of the machine used

Table1: Machining process parameters levels

Parameter	Unit	1	2	3	4
Work speed(*N*)	rpm	56	80	112	160
Long. Feed(*f*)	mm/rev	11.33	17.00	22.66	28.3
Radial infeed(*d*)	mm	0.02	0.04	0.06	0.08

3.1 Work piece material

The present study is carried out with AISI 1040 mild steel specimens. The chemical composition of AISI 1040 steel is given as follows: 0.42%C, 0.48%Mn, 0.17%Si, 0.02%P, 0.018%S, 0.1%Cu, 0.09%Ni, 0.07%Cr and balance Fe.The physical properties are as follows: Hardness-201 BHN, Density-7.85 g/cc, Tensile strength-620 MPa. All the specimens are in the form of round bars of diameter 48 mm and length 50 mm.

3.2. Response variables

The response variables used to accomplish the present study on surface roughness are the following: Centre line average roughness (R_a), Root mean square roughness (R_q), Skewness (R_{sk}), Kurtosis (R_{ku}), Mean line peak spacing (R_{sm}).

4. RESULTS AND DISCUSSION

All the experiments have been conducted in a HMT made (model K130U) cylindrical grinding machine as per the design of experiment with random order and the surface parameters have been measured using the stylus-type profilometer, Talysurf (Taylor Hobson, Surtronic 3+). The measured roughness parameters have been shown in Table 2 for mild steel. The results are put into the Minitab software for further analysis. The second order model was postulated in obtaining the relationship between the surface roughness parameters and the machining variables. The analysis of variance (ANOVA) was used to check the adequacy of the second order model.

The second order response surface equations have been fitted using Minitab software for all the five response variables (R_a, R_q, R_{sk}, R_{ku} and R_{sm}). The equations can be given in terms of the independent variables as the following:

$$\begin{aligned} R_a &= 0.6297 - 0.0786N + 0.1796f + 0.082d \\ &+ 0.0505Nf + 0.0251Nd + 0.0136fd \qquad (3) \\ &- 0.01N^2 - 0.0378f^2 - 0.0086d^2 \end{aligned}$$

$$\begin{aligned} R_q &= 0.7226 - 0.0805N + 0.2236f + 0.164d \\ &+ 0.0623Nf + 0.029Nd + 0.0127fd \qquad (4) \\ &- 0.0136N^2 - 0.0444f^2 - 0.0198d^2 \end{aligned}$$

$$R_{sk} = -0.3068 + 0.2525N - 0.3059f + 0.4594d + 0.003Nf - 0.0107Nd - 0.0448fd - 0.0498N^2 + 0.0878f^2 - 0.055d^2 \quad (5)$$

$$R_{ku} = 2.331 + 1.2921N - 0.6016f + 0.291d - 0.0758Nf + 0.0126Nd + 0.0327fd - 0.2072N^2 + 0.1618f^2 - 0.0879d^2 \quad (6)$$

$$R_{sm} = 0.0526 - 0.0022N + 0.0018f + 0.0012d + 0.001Nf - 0.0001Nd + 0.0002fd - 0.0001N^2 - 0.0005f^2 + 0.00006d^2 \quad (7)$$

Analysis of variance (ANOVA) technique is used to check the adequacy of the developed models at 95% confidence level. As per this technique, if the calculated value of the *F*-ratio of the regression model is more than the standard tabulated value of table (*F*-table) for 95% confidence level, then the model is considered adequate within the confidence level.

Table 2: Experimental results of roughness parameters

Std. order	**R_a(μm)**	**R_q(μm)**	**R_{sk}**	**R_{ku}**	**R_{sm} (mm)**
1	0.869	1.090	-0.164	3.47	0.054
2	0.919	1.172	0.361	3.84	0.050
3	1.135	1.540	1.686	3.45	0.066
4	1.177	1.487	0.268	3.39	0.052
5	0.725	0.915	-0.202	3.23	0.055
6	1.066	1.337	-0.136	2.97	0.062
7	0.969	1.230	0.074	3.86	0.054
8	1.270	1.587	0.188	3.24	0.066
9	1.152	1.460	0.365	3.66	0.050
10	1.270	1.622	0.532	4.22	0.058
11	1.174	1.477	0.295	3.16	0.060
12	1.417	1.760	0.256	3.11	0.056
13	0.974	1.235	-0.010	3.53	0.057
14	1.280	1.615	0.334	3.78	0.056
15	1.222	1.632	0.755	7.15	0.061
16	1.140	1.427	0.094	3.48	0.058
17	0.875	1.092	0.204	3.49	0.050
18	1.012	1.292	0.323	4.01	0.055
19	0.906	1.162	0.259	3.62	0.054
20	1.172	1.517	0.613	4.69	0.052
21	0.805	1.015	-0.113	3.26	0.058
22	1.197	1.490	0.205	3.21	0.060
23	1.282	1.625	0.167	3.94	0.066
24	1.395	1.747	0.094	2.98	0.071
25	1.102	1.390	-0.046	3.26	0.052
26	1.166	1.477	0.276	4.03	0.053
27	1.490	1.912	0.716	3.96	0.068
28	1.645	2.065	0.474	3.51	0.063
29	1.330	1.685	0.310	3.87	0.058
30	1.515	1.950	0.839	7.75	0.055
31	1.357	1.717	-0.182	3.49	0.056
32	1.512	1.957	0.317	4.59	0.064
33	0.823	1.063	0.096	3.90	0.050
34	0.739	0.990	1.128	4.75	0.045
35	0.891	1.129	0.001	3.38	0.048
36	0.897	1.156	0.069	3.67	0.056
37	0.849	1.057	0.030	3.28	0.050
38	1.205	1.560	0.176	4.11	0.052
39	1.287	1.760	1.437	3.31	0.055
40	1.542	1.922	-0.113	2.92	0.052
41	1.525	1.925	0.291	3.22	0.058
42	1.217	1.567	0.187	3.70	0.050
43	1.745	2.180	0.218	3.29	0.059
44	1.897	2.392	0.201	3.53	0.059
45	0.995	1.380	1.779	3.44	0.064
46	1.111	1.385	-0.130	3.31	0.062
47	1.365	1.740	0.374	4.48	0.067
48	1.575	1.985	0.281	3.59	0.062
49	0.936	1.192	0.317	3.45	0.053
50	1.033	1.322	0.384	3.94	0.050
51	1.018	1.302	0.386	3.35	0.051
52	1.112	1.412	0.277	3.33	0.054
53	0.847	1.084	-0.171	3.74	0.054
54	1.195	1.507	0.039	3.83	0.054
55	1.365	1.810	-0.558	3.59	0.057
56	1.372	1.727	0.336	3.36	0.054
57	0.777	1.017	-0.032	4.21	0.050
58	1.392	1.852	0.502	3.44	0.065
59	1.320	1.690	0.421	3.99	0.053
60	1.655	2.110	0.470	3.59	0.065
61	1.390	1.757	-0.118	3.19	0.058
62	1.817	2.282	0.320	3.34	0.055
63	1.720	2.155	0.256	3.46	0.062
64	2.075	2.605	0.369	3.92	0.067

From Tables 3, 5, 7, 9 and 11, it is observed that surface roughness models are adequate at 95% confidence level. Further, it is necessary that residuals should be normally distributed in order that the regression analysis is valid. The accuracy of the models has been checked by the complete residual analysis. The normal probability plots for centre line average clearly demonstrate that the residuals closely follow a straight line, denoting a normal distribution as shown in Fig. 1. All the statistical measures as explained above show that the non-linear relationships between the factors (*N*, *f*, and *d*) and the responses (R_a, R_q, R_{sk}, R_{ku} and R_{sm}) are adequate regression models. Tables 4, 6, 8, and10 are present ANOVA tables for individual parameters. The significant effect of individual and interaction terms is shown in the summary Table 13. The longitudinal feed is the most influential factor for all surface roughness parameters except $R_{ku.}$ Similarly, radial infeed is significant for all surface roughness parameters except R_{sk} and $R_{ku.}$ Workpiece speed is significant for R_a, R_q and R_{ku}. The main effect plots of surface roughness parameters with process variables are shown in the Fig. 2. It reveals the same results as explained in ANOVA tables. The parametric analysis has been carried out to study the influence of the individual process parameters such as workpiece speed, longitudinal feed and radial infeed on the surface roughness parameters during cylindrical grinding based on the developed empirical models as established through RSM and response surface plot using

MATLAB software.

Table 3: ANOVA for model of R_a in mild steel

Source	DF	SS	MS	F	P
Regression	9	4.03	0.44	15.07	0.000
Linear	3	3.59	0.03	1.01	0.395
Square	3	0.11	0.03	1.15	0.336
Interaction	3	0.33	0.11	3.78	0.015
Residual Error	54	1.60	0.03		
Total	63	5.64			

Table 4: ANOVA for individual parameter of R_a

Source	df	SS	MS	F	P
N	3	0.33	0.11	7.69	0.001
f	3	1.96	0.65	44.4	0.000
d	3	1.52	0.50	34.46	0.000
$N*f$	9	0.96	0.10	7.31	0.000
$N*d$	9	0.20	0.02	1.55	0.180
$f*d$	9	0.24	0.02	1.87	0.101
Error	27	0.39	0.01		
Total	63	5.64			

Table 5: ANOVA for model of R_q

Source	DF	SS	MS	F	
Regression	9	6.33	0.70	15.18	0.000
Linear	3	5.67	0.05	1.15	0.338
Square	3	0.16	0.05	1.17	0.328
Interaction	3	0.48	0.16	3.52	0.021
Residual Error	54	2.50	0.04		
Total	63	8.83			

Table 6: ANOVA for individual parameter of R_q

Source	DF	SS	MS	F	P
N	3	0.57	0.19	6.97	0.00
f	3	3.06	1.02	37.30	0.00
d	3	2.36	0.78	28.76	0.00
$N*f$	9	1.40	0.15	5.69	0.00
$N*d$	9	0.32	0.03	1.31	0.27
$f*d$	9	0.35	0.03	1.44	0.21
Error	27	0.74	0.02		
Total	63	8.83			

Table 7: ANOVA for model of R_{sk}

Source	DF	SS	MS	F	P
Regression	9	5.48	0.60	5.46	0.005
Linear	3	0.25	0.08	0.75	0.291
Square	3	0.84	0.28	2.52	0.047
Interaction	3	0.21	0.07	0.63	0.594
Residual Error	54	6.01	0.11		
Total	63	12.81			

Table 8: ANOVA for individual parameter of R_{sk}

Source	DF	SS	MS	F	P
N	3	0.17	0.05	0.53	0.66
f	3	1.09	0.36	3.25	0.03
d	3	0.36	0.12	1.09	0.36
$N*f$	9	0.47	0.05	0.47	0.88
$N*d$	9	1.47	0.16	1.46	0.21
$f*d$	9	0.70	0.07	0.7	0.70
Error	27	3.02	0.11		
Total	63	7.32			

Table 9: ANOVA for model of R_{ku}

Source	DF	SS	MS	F	P
Regression	9	12.27	1.36	3.30	0.016
Linear	3	1.65	0.55	1.34	0.030
Square	3	4.91	1.63	3.97	0.018
Interaction	3	0.69	0.23	0.56	0.673
Residual Error	54	22.27	0.41		
Total	63	41.81			

Table 10: ANOVA for individual parameter of R_{ku}

Source	DF	SS	MS	F	P
N	3	5.40	1.80	4.13	0.016
f	3	2.47	0.82	1.89	0.155
d	3	1.19	0.39	0.92	0.447
$N*f$	9	4.56	0.50	1.16	0.357
$N*d$	9	3.81	0.42	0.97	0.483
$f*d$	9	2.30	0.25	0.59	0.796
Error	27	11.77	0.43		
Total	63	31.54			

Table 11: ANOVA for model of R_{sm}

Source	DF	Seq SS	Adj MS	F	P
Regression	9	0.000835	0.000093	4.2	0.000
Linear	3	0.000694	0.000007	0.33	0.803
Square	3	0.000022	0.000007	0.34	0.799
Interaction	3	0.000118	0.000039	1.78	0.162
Residual Error	54	0.001194	0.000022		
Total	63	0.002029			

Table 12: Summary of ANOVA for roughness parameters

	N	f	d	$*f$	$N*d$	$f*d$
R_a	#	#	#	#		
R_q	#	#	#	#		
R_{sk}		#				
R_{ku}	#					
R_{sm}		#	#			

#-Significant parameter

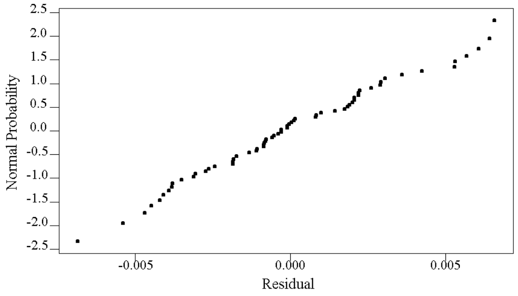
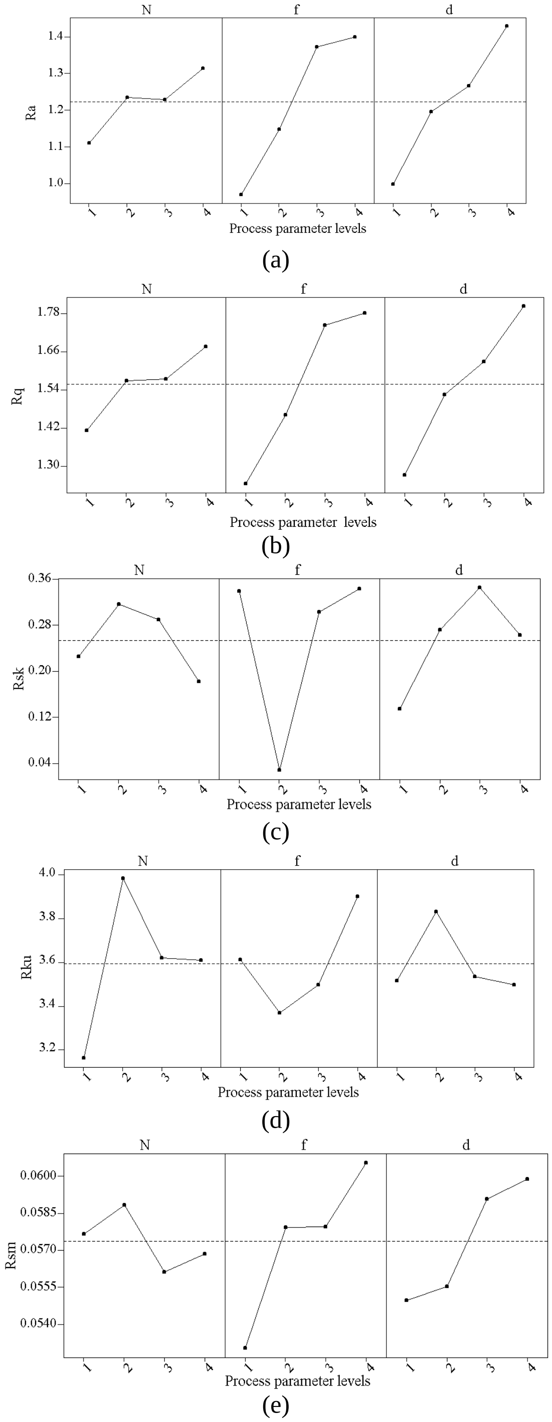


Fig 1. Normal probability plot of residuals of R_a



(a)

(b)

(c)

(d)

(e)

Fig 2. Main effect plots of surface roughness parameters

The three dimensional surface plots and contour plots for the five roughness parameters (R_a, R_q, R_{sk}, R_{ku}, and R_{sm}) are shown in Figs. 3-7. In each of the plots, two cutting parameters are varied while the third one is held at its mid value. It is seen from these plots that there is significant amount of curvature indicating non-linearity in the variation.

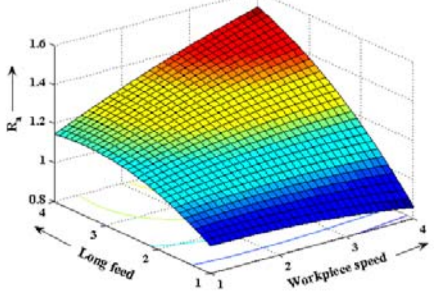


Fig 3. Surface and contour plots for R_a in cylindrical grinding of mild steel

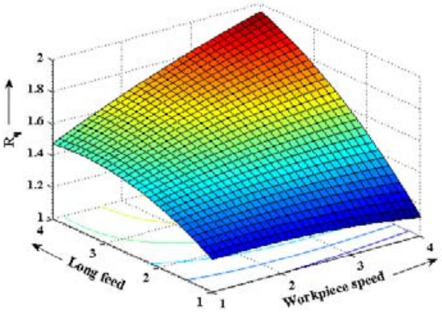


Fig 4. Surface and contour plots for R_q in cylindrical grinding of mild steel

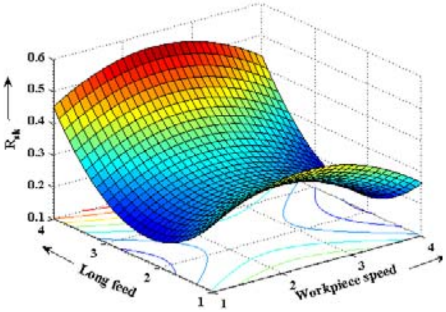


Fig 5. Surface and contour plots for R_{sk} in cylindrical grinding of mild steel

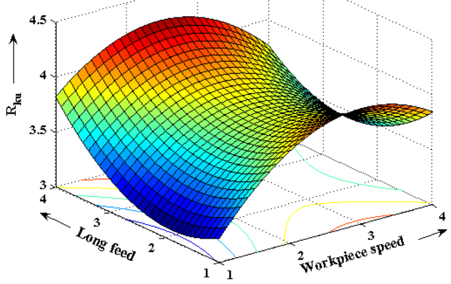


Fig 6. Surface and contour plots for R_{ku} in cylindrical

grinding of mild steel

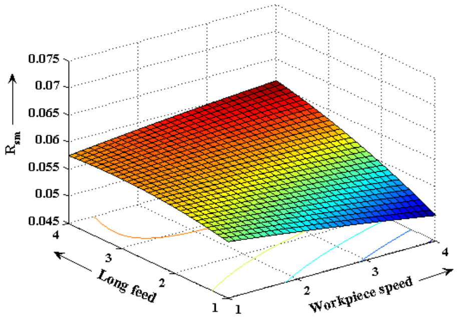


Fig 7. Surface and contour plots for R_{sm} in cylindrical grinding of mild steel

For some plots, e.g., Fig. 3, 4 and 6 there is switching of the curvature effect. It indicates the reversal in behaviour depending on the combination of the machining parameters. It also points towards significant contribution from the interaction of the machining parameters.

Optimization of machining parameters increases the utility for machining economics; a response surface optimization is attempted using Minitab software for individual roughness parameters in cylindrical grinding. Table 13 shows the RSM optimization results for the roughness parameters in mild steel grinding. It also includes the results from confirmation experiments conducted with the optimum conditions. It is found that the error in prediction of the optimum conditions for different roughness parameters individually is about 3 to 6%. Thus the response optimization predicts the optimum conditions fairly well.

Table 13 RSM optimization for roughness parameters

Para-meter	**Objective func.**	**Optimum combination**			**Predi. response**	**Expt. value**	**% of error**
		N	*f*	*d*			
R_a	min	58.12	12.44	0.03	0.765	0.811	-6.01
R_q	min	62.23	15.45	0.05	0.964	1.024	-6.22
R_{sk}	Tar. 0	82.32	26.23	0.06	0.031	0.033	-6.45
R_{ku}	Tar. 3	141.55	16.23	0.07	3.12	3.22	-3.21
R_{sm}	min	142.85	22.25	0.04	0.023	0.024	-4.35

5. CONCLUSION

In this study an experimental investigation performed to evaluate the surface roughness parameters of AISI 1040 mild steel in grinding operation has been presented. A plan of experiments has been prepared in order to test the influence of cutting speed, longitudinal feed and radial infeed on the surface roughness parameters. The obtained data have been statistically processed using response surface method. The empirical models of roughness parameters are established and tested through the analysis of variance to validate the adequacy of the models. It is found that the roughness parameters greatly depend on workpiece materials.

6. REFERENCES

1. Kwak, J.S., 2005, “Application of Taguchi and response surface methodologies for geometric error in surface grinding process”, International Journal of Machine Tools & Manufacture, 45:327-334.
2. Kwak, J.S., Sim, S.B. and Jeong, Y.D., 2006, “An analysis of grinding power and surface roughness in external cylindrical grinding of hardened SCM440 steel using the response surface method”, International Journal of Machine Tools & Manufacture, 46:304-312.
3. Shaji, S. and Radhakrishnan, V., 2003, “Analysis of process parameters in surface grinding with graphite as lubricant based on the Taguchi method”, Journal of Materials Processing Technology, 141:51-59.
4. Dhavlikar, M.N., Kulkarni, M.S. and Mariappan, V., 2003, “Combined Taguchi and dual response method for optimization of a centerless grinding operation”, Journal of Materials Processing Technology, 132:90-94.
5. Hecker, R.L. and Liang, S.Y., 2003, “Predictive modelling of surface roughness in grinding”, International Journal of Machine Tools & Manufacture, 43:755-761.
6. Zhong, Z.W., Khoo, L.P. and Han, S.T., 2006, “Prediction of surface roughness of turned surfaces using neural networks”, International Journal of Advanced Manufacturing Technology, 28:688-693.
7. Sun, X., Stephenson, D.J., Ohnishi, O. and Baldwin, A., 2006, “An investigation into parallel and cross grinding of BK7 glass”, Precision Engineering, 30:145-153.
8. Atzeni, E. and Iuliano, L., 2008, “Experimental study on grinding of a sintered friction material”, Journal of Materials Processing Technology, 196:184-189.
9. Choi, T.J., Subrahmanya, N., Li, H. and Shin, Y.C., 2008, “Generalized practical models of cylindrical plunge grinding process”, International Journal of Machine Tools and Manufacture, 48:61-72.
10. Liu, C.H., Chen, A., Chen, C.A. and Wang, Y.T., 2005, “Grinding force control in an automatic surface finishing system”, Journal of Materials Processing Technology, 170:367-373.
11. Montegomery. D. C., 1991, Design and Analysis of experiments, Wiley, India.

7. MAILING ADDRESS:

B. C.Routara
Department of Mechanical Engineering, KIIT University, Bhubaneswar-751024
E-mail: bharat_routray@rediffmail.com