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Hybrid optimal scheme for minimizing machining force and surface roughness in hard turning of AISI 52100 steel

P. Umamaheswarrao[a*], D. Ranga Raju[b], K.N.S. Suman[c], B. Ravi Sankar[d]

[a*]*Department of Mechanical Engineering, Bapatla Engineering College, Bapatala, A.P INDIA*
[b]*Department of Mechanical Engineering, Srinivasa Institute of Engineering and Technology, Amalapuram, A.P INDIA*
[c]*Department of Mechanical Engineering, College of Engineering Andhra University, A.P INDIA*
[d]*Department of Mechanical Engineering, Bapatla Engineering College, Bapatala, A.P INDIA*
[*]*Corresponding Author: e-mail: maheshponugoti@gmail.com, Tel +91-9440871256*

Abstract

In the present work hard turning of AISI 52100 steel has been performed using PCBN tools. The input parameters considered are cutting speed, feed, depth of cut, Nose radius and negative rake angle and the measured responses are machining force (F_M) and surface roughness (Ra). Experiments are planned as per Center Composite rotatable Design (CCD) of Response Surface Methodology (RSM). Investigative analysis on the effect of input parameters on the response is carried out using main effects plot and response surface plots. Further, a multi-objective optimization is performed with RSM and Grey Relational Analysis (GRA) integrated with Principle Component Analysis (PCA). Results demonstrated that negative rake angle is the paramount factor affecting the response followed by feed, speed, depth of cut, and nose radius. The optimum cutting parameters obtained are cutting speed 1000 rpm, feed 0.02 mm/rev, depth of cut 0.4 mm, Nose radius 1 mm and Negative rake angle 5°

Keywords: Hard turning, AISI 52100 steel, Machining force, Surface roughness, Grey relational analysis.

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1. Introduction

Turning of hardened steels with hardness greater than 45 HRC is known as hard turning. Grinding is replaced by hard turning for hardened steel for finishing operations due to its process flexibility, high material removal rate, short cycle time and absence of coolant (König et al. 1984; Tönshoff et al. 2000). The differences between conventional machining vs hard turning was given away in Fig.1. (Dogra et al., 2010). Fabrication of complex parts with the help of hard turning leads to reduction of manufacturing cost by 30% (Huang et al., 2007). Meddour et al. (2015) revealed that the force components were notably influenced by depth of cut followed by feed rate during AISI 52100 hard turning. Vrabeľ et al. (2016) reported that surface roughness was highly affected by feed rate than cutting speed. Further, the feed rate was the most considerable factor for minimizing cutting force components. Ildikó et al. (2016) disclosed that surface roughness and cutting force components is influenced by cutting speed and feed in hard turning with coated ceramics. Azizi et al. (2016) observed that cutting forces increased as a function of work piece hardness and cutting time when turning was carried out with TiN coated ceramic inserts. Ouahid et al. (2017) noticed that feed rate has the major influence on surface quality and cutting force components majorly influenced by depth of cut.

Bartarya and Choudhury (2014) conducted the study with uncoated CBN tool and observed that feed and depth of cut were the most significant parameters affecting the forces. Surface roughness was highly influenced by depth of cut. In hard turning of AISI 52100 steel with PCBN tool feed rate has a significant influence on the surface finish while cutting speed and depth of cut had marginal effect (Gabriel et al., 2015), the tool geometry nose radius had a great influence (Ravi Sankar and Umamaheswarrao, 2017). Saurabh et al. (2018) optimized machining parameters during turning of hard porcelain using Taguchi and Response surface methodology. GRA coupled with PCA for multi-objective optimization of parameters was performed by Pradhan (2013), Vijian and Seshagiri Rao (2015), Umamaheswarrao et al. (2018) and gained wider success.

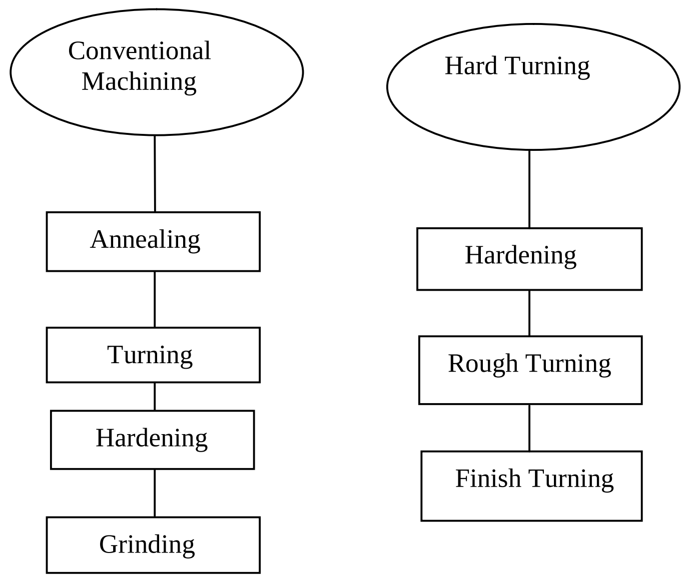

Figure 1. Distinction between conventional machining and hard turning (Dogra et al., 2010)

From the literature, it was elucidated that hard turning was the best alternative to grinding owing to its merits. Much emphasis was made on hard tuning of AISI 52100 steel by several researchers due to its applications in various parts of industry. The past studies made a large amount of interest to investigate the effect of cutting parameters on the responses. However, small insight was put on the investigations related to tool geometry such as nose radius, negative rake angle etc. Numerous authors adopted various optimization techniques for improving machining performance and integration of RSM, GRA and PCA was rarely deployed. Hence, the present study was aimed to conduct AISI 52100 steel hard turning using PCBN tools with cutting speed, feed rate and depth of cut as cutting conditions, nose radius and negative rake angle as tool parameters. Machining force and surface roughness were considered as responses. Further, multi response optimization was performed by integrating RSM, GRA and PCA for optimum cutting conditions.

2. Experimental Details

2.1 Workpiece

AISI 52100 steel is used as workpiece with a length of 500 mm and diameter of 48 mm. Length of machining was 30 mm for each experimental run. Hardness of the workpiece used is 57 HRC.

Table 1. Factors and their levels

S.No	Factors	Notation	Levels				
			-2	-1	0	1	2
1	Speed (rpm)	ν	200	400	600	800	1000
2	Feed (mm/rev)	f	0.02	0.04	0.06	0.08	0.1
3	Depth of Cut (mm)	d	0.4	0.5	0.6	0.7	0.8
4	Nose radius (mm)	r	0.4	0.6	0.8	1	1.2
5	Negative rake angle (^{o})	α	-5	-15	-25	-35	-45

2.2 Cutting tool

PCBN tool (Fig.2) with different nose radii i.e. 0.4, 0.6, 0.8, 1, 1.2 mm is deployed for experimentation with varied negative rake angles -5, -15, -25, -35, -45. ISO Geometric designations of the inserts are CNMG 120404, CNMG 120406, CNMG 120408, CNMG 120410 and CNMG 120412.

In dry condition experiments were carried out using on Kirloskar Turn master-35 type lathe. PSBNR2525 M12 type tool holder was used for mounting inserts. Experimental setup was shown in Fig.3. The initial cutting parameters were selected as cutting speed 200 rpm, feed 0.02 mm/rev, depth of cut 0.4 mm, nose radius 0.4 mm and negative rake angle 5º. Factors and their levels are given away in Table 1. Kistler three-component measuring system (model 9257B) was used to measure cutting forces. The turned samples surface roughness was measured with Mitutoyo make Surface roughness tester (SJ-210). Experimental matrix with obtained responses is given in Table 2.

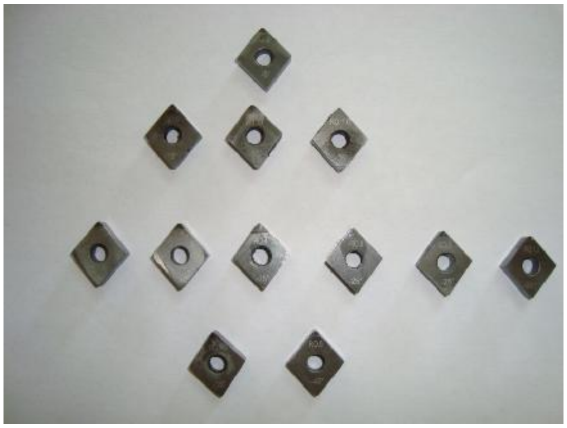

Figure 2. PCBN tools

Figure 3. Experimental setup

3. Methodology Adopted

3.1 Hybrid GRA-PCA

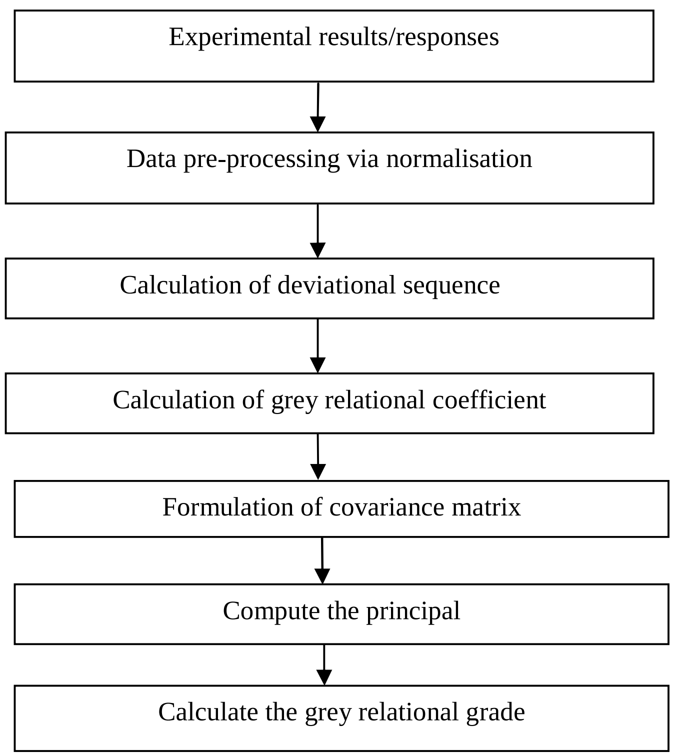

Figure 4. Steps in hybrid GRA-PCA

Optimum combination of various input parameters are determined by deploying GRA and PCA to obtain the best quality characteristics. (Wang et al., 2013; Hotelling H., 1993). Steps in hybrid GRA-PCA is given away in Fig.4. Normalized values and Deviational sequences are given away in Table 3.

Table 2. Experimental matrix with responses

Exp. No	ν (rpm)	f (mm/rev)	d (mm)	r (mm)	α (°)	F_M (N)	Ra (µm)
1	400	0.04	0.5	0.6	35	404.735	0.525
2	800	0.04	0.5	0.6	15	233.475	0.465
3	400	0.08	0.5	0.6	15	322.117	0.453
4	800	0.08	0.5	0.6	35	473.03	0.545
5	400	0.04	0.7	0.6	15	317.493	0.552
6	800	0.04	0.7	0.6	35	376.384	0.507
7	400	0.08	0.7	0.6	35	583.032	0.539
8	800	0.08	0.7	0.6	15	380.407	0.471
9	400	0.04	0.5	1	15	273.585	0.485
10	800	0.04	0.5	1	35	425.463	0.401
11	400	0.08	0.5	1	35	561.163	0.507
12	800	0.08	0.5	1	15	350.276	0.502
13	400	0.04	0.7	1	35	443.782	0.508
14	800	0.04	0.7	1	15	323.621	0.408
15	400	0.08	0.7	1	15	411.791	0.604
16	800	0.08	0.7	1	35	523.367	0.498
17	200	0.06	0.6	0.8	25	430.828	0.559
18	1000	0.06	0.6	0.8	25	355.441	0.456
19	600	0.02	0.6	0.8	25	309.595	0.468
20	600	0.1	0.6	0.8	25	534.481	0.53
21	600	0.06	0.4	0.8	25	344.431	0.45
22	600	0.06	0.8	0.8	25	449.219	0.48
23	600	0.06	0.6	0.4	25	359.396	0.514
24	600	0.06	0.6	1.2	25	446.225	0.485
25	600	0.06	0.6	0.8	5	279.954	0.484
26	600	0.06	0.6	0.8	45	601.276	0.509
27	600	0.06	0.6	0.8	25	358.525	0.507
28	600	0.06	0.6	0.8	25	370.743	0.518
29	600	0.06	0.6	0.8	25	378.525	0.52
30	600	0.06	0.6	0.8	25	403.976	0.512
31	600	0.06	0.6	0.8	25	380.24	0.488
32	600	0.06	0.6	0.8	25	370.65	0.522

The obtained Eigen values and Eigen vectors are shown in Table 4 & Table 5. The GRC and GRG for the experimental runs are shown in Table 6. Fig.5 shows the variation of GRG with an experimental run.

Table 3. Normalized values and Deviational sequences

	Normalized Values		Deviation Sequences	
Exp. No	Machining force	Surface roughness	Machining force	Surface roughness
1	0.53436	0.389162	0.46563	0.610837
2	1	0.684729	0	0.315270
3	0.758994	0.743842	0.241005	0.256157
4	0.348683	0.290640	0.651316	0.709359
5	0.77156	0.256157	0.22843	0.743842
6	0.611450	0.477832	0.388549	0.522167
7	0.04960	0.320197	0.95039	0.679802
8	0.600512	0.655172	0.399487	0.344827
9	0.890946	0.586206	0.109053	0.413793
10	0.478011	1	0.521988	0
11	0.109061	0.477832	0.890938	0.522167
12	0.682434	0.502463	0.317565	0.497536
13	0.428204	0.472906	0.571795	0.527093
14	0.754905	0.965517	0.245094	0.034482
15	0.515183	0	0.484816	1
16	0.211823	0.522167	0.788176	0.477832
17	0.463424	0.221674	0.536575	0.778325
18	0.668391	0.729064	0.331608	0.270935
19	0.793040	0.669950	0.206959	0.330049
20	0.181606	0.36453	0.818393	0.63546
21	0.698325	0.75862	0.301674	0.24137
22	0.413421	0.610837	0.586578	0.389162
23	0.657638	0.443349	0.342361	0.556650
24	0.421562	0.586206	0.578437	0.413793
25	0.873630	0.591133	0.126369	0.408866
26	0	0.467980	1	0.532019
27	0.660006	0.477832	0.339993	0.522167
28	0.626787	0.42364	0.373212	0.57635
29	0.605629	0.413793	0.394370	0.586206
30	0.536431	0.45320	0.463568	0.54679
31	0.600966	0.571428	0.399033	0.428571
32	0.627040	0.403940	0.372959	0.596059

Table 4. Eigen values and explained variation for Principal components

Principal component	Eigen value	Explained Variations (%)
First	1.2406	64.03
Second	0.6969	35.96

Table 5. The Eigenvectors for principal components and contribution

Responses	Eigenvectors		Contribution
	First principal component	Second principal component	
Machining force	0.7071	-0.7071	0.49999
Surface roughness	0.7071	0.7071	0.49999

Table 6. GRC, GRG and rank of the Machining force, Surface roughness

Exp. No	GRC		GRG	Rank
	Machining force	Surface roughness		
1	0.5177955	0.450110865	0.483943	23
2	1	0.613293051	0.80663	1
3	0.674759	0.661237785	0.667985	6
4	0.4342853	0.413441955	0.423855	28
5	0.6864046	0.401980198	0.544182	13
6	0.5627147	0.489156627	0.525925	16
7	0.3447332	0.423799582	0.384259	32
8	0.5558719	0.591836735	0.573843	10
9	0.8209459	0.547169811	0.684044	4
10	0.4892422	1	0.744606	3
11	0.3594696	0.489156627	0.424305	27
12	0.6115716	0.501234568	0.556392	11
13	0.4665069	0.486810552	0.476649	24
14	0.6710558	0.935483871	0.803254	2
15	0.5077088	0.333333333	0.420513	29
16	0.3881457	0.511335013	0.449731	25
17	0.4823575	0.391136802	0.436738	26
.18	0.6012443	0.6485623	0.624891	9
19	0.7072539	0.602373887	0.654801	7
20	0.3792494	0.440347072	0.40979	30
21	0.6236949	0.674418605	0.649044	8
22	0.4601602	0.56232687	0.511233	19
23	0.5935692	0.473193473	0.533371	15
24	0.4636336	0.547169811	0.505392	21
25	0.7982503	0.550135501	0.674179	5
26	0.3333333	0.484486874	0.408902	31
27	0.5952426	0.489156627	0.542189	14
28	0.5725982	0.464530892	0.518554	17
29	0.5590522	0.46031746	0.509675	20
30	0.5189044	0.477647059	0.498266	22
31	0.5561527	0.538461538	0.547296	12
32	0.572764	0.456179775	0.514462	18

Table 7. Mean response table for GRG

Level	ν	f	d	r	α
1	0.436738	0.654801*	0.649044*	0.533371	0.674179*
2	0.510735	0.633654	0.59897	0.551328	0.632105
3	0.620178	0.533871	0.527036	0.535716	0.53255
4	0.510735	0.48761	0.522295	0.569937*	0.489159
5	0.624891*	0.40979	0.511233	0.505392	0.408902
Delta	0.188153	0.245011	0.137811	0.064545	0.265277
Rank	3	2	4	5	1

4. Results and Discussion

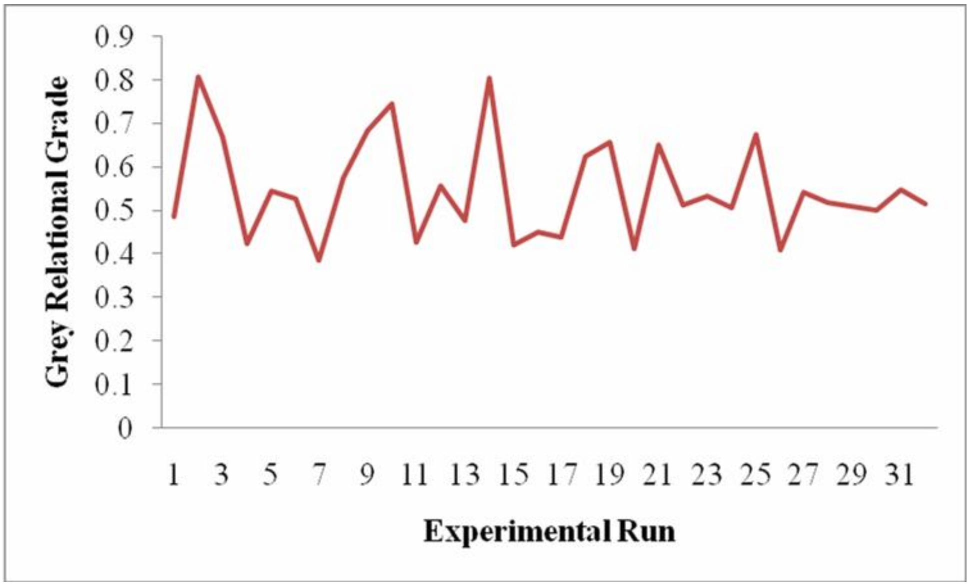

Figure 5. Experimental Run Vs GRG

The larger GRG indicates the better multiple-performance characteristics and therefore, the levels at which the largest average response was obtained was selected. In the response table (Table 7) negative rake angle has been assigned a rank 1 hence, it is the paramount parameter in controlling the response followed by feed, speed, depth of cut, and nose radius. From the ANOVA analysis, it is clear that negative rake angle contribution is highest (34.03%) followed by feed (33.53%), speed (17.55%), depth of cut (12.12%) and nose radius (2.24%) as shown Table 8. Estimated regression coefficients for GRG are shown in Table 9.

Table 8. ANOVA for GRG

Source	DF	SS	MS	F	P	% Contribution
Speed	4	0.0634	0.0158	1.27	0.307	17.55
Feed	4	0.1211	0.0303	2.92	0.040	33.53
Depth of cut	4	0.0438	0.0109	0.83	0.520	12.12
Nose radius	4	0.0081	0.0020	0.14	0.967	2.24
Negative rake angle	4	0.1229	0.0307	2.98	0.037	34.03
Error	11	0.0018	0.0004			0.49

The regression coefficients are estimated for responses and the modeling is done considering 95% confidence level and hence those terms having P value >0.05 are insignificant. The adequacy of the developed model is judged by the R^2 value and is 98.7% which is beyond 75% indicates the model is in good agreement. Quadratic equation for GRG after eliminating insignificant terms is shown below

$$GRG = 0.519009+0.097888*v-0.138198*f-0.074085*d+0.007743*r-0.139510*\alpha+0.069325*d*d-0.146210*v*f+0.063986*v*d+0.074647*v*r-0.136719*f*r+0.101436*r*\alpha \quad (1)$$

From the main effect plot (Fig.6), it is observed that the optimistic grey relational grade can be achieved with Speed = 1000 rpm, feed = 0.02 mm/rev, depth of cut=0.4 mm, nose radius= 1 mm, negative rake angle = 5° respectively.

From the response plots (shown in Figure 7) it is evident that higher GRG was noticed at higher limits of speed, nose radius and negative rake angle and at lower limits of depth of cut and feed. Nose radius exhibited interaction with speed, feed and negative rake angle.

GRG for the obtained optimum combination of parameters was 0.98424 estimated from Eq. 2 and was 22.01% higher than highest GRG in Table 6, which indicates confirmation of optimality.

$$¥ = ¥_m + \sum_{i=1}^{q} (\overline{¥_j} - ¥_m) \quad (2)$$

Table 9. Estimated Regression Coefficients for GRG

Term	Coef	SE Coef	T	P
Constant	0.519009	0.008703	59.633	0.000
ν	0.097888	0.008908	10.989	0.000
f	-0.138198	0.008908	-15.514	0.000
d	-0.074085	0.008908	-8.317	0.000
r	0.007743	0.008908	0.869	0.403
α	-0.139510	0.008908	-15.661	0.000
ν * ν	0.020001	0.016115	1.241	0.240
f*f	0.021482	0.016115	1.333	0.209
d*d	0.069325	0.016115	4.302	0.001
r*r	0.008568	0.016115	0.532	0.606
α*α	0.030727	0.016115	1.907	0.083
ν *f	-0.146210	0.021820	-6.701	0.000
ν*d	0.063986	0.021820	2.932	0.014
ν*r	0.074647	0.021820	3.421	0.006
ν * α	-0.012108	0.021820	-0.555	0.590
f*d	0.031255	0.021820	1.432	0.180
f*r	-0.136719	0.021820	-6.266	0.000
f*α	0.017601	0.021820	0.807	0.437
d*r	0.023751	0.021820	1.088	0.300
d*α	0.033278	0.021820	1.525	0.155
r*α	0.101436	0.021820	4.649	0.001
S = 0.02182 R-Sq = 98.7% R-Sq(adj) = 96.3%				

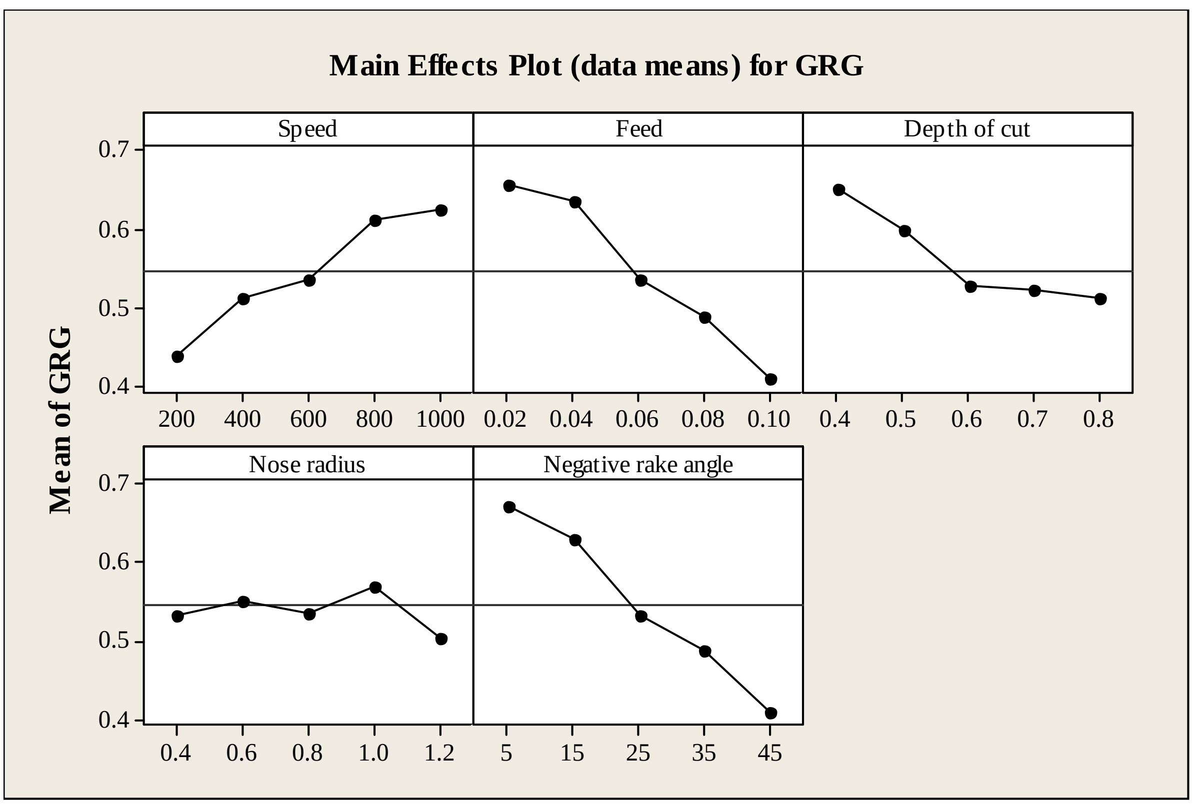

Figure 6. Main effects plot for GRG

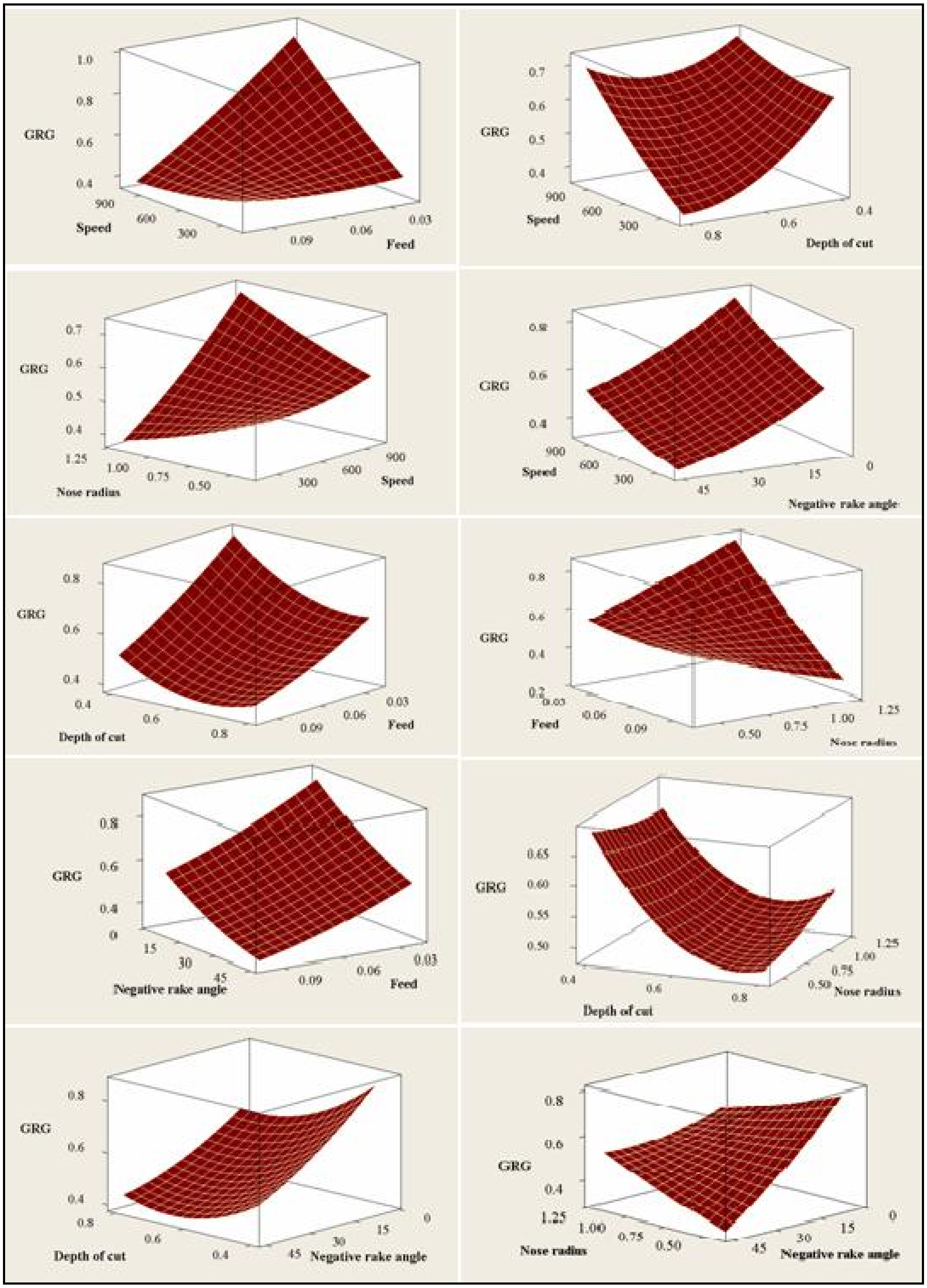

Figure 7. Response plots for GRG [Hold Values Speed 600; Feed 0.06; Depth of cut 0.6; Nose radius 0.8; Negative rake angle 25°]

5. Conclusions

The optimization of parameters in hard turning of AISI 52100 steel was carried out with multiple performance characteristics. The experiments were conducted as per Center Composite Rotatable Design (CCD) of RSM and multi-objective optimization was performed using GRA coupled with PCA.

- Optimum parametric settings and their levels were A5B1C1D4E1 i.e (Speed =1000 rpm, feed = 0.02 mm/rev, depth of cut = 0.4 mm, Nose radius = 1 mm and Negative rake angle = 5^{o}).
- Responses were most significantly affected by negative rake angle followed by feed, speed, depth of cut, and nose radius.
- The interaction effect was found among speed and nose radius, nose radius and negative rake angle, feed and nose radius.

Nomenclature

RSM	Response Surface Method
GRG	Grey Relation Grade
GRA	Grey Relation Analysis
GRC	Grey Relation Coefficient
PCA	Principle Component Analysis
ANOVA	Analysis of Variance
CBN	cubic boron nitride
PCBN	Polycrystalline cubic boron nitride
¥	Predicted Grey relational grade
¥$_m$	Total mean of Grey relational grade
$\overline{¥}_j$	Mean of Grey relational grade at the optimal level

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Biographical notes

P. Umamaheswarrao and **B. Ravi Sankar** are of the Department of Mechanical Engineering, Bapatla Engineering College, Bapatala, India.

D. Ranga Raju is of the Department of Mechanical Engineering, Srinivasa Institute of Engineering and Technology, Amalapuram, A.P India

K.N.S. Suman is of the [c]Department of Mechanical Engineering, College of Engineering Andhra University, A.P India

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