Application of TOPSIS for multi response optimization of Process Parameters in dry hard turning of AISI 52100 steel

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Abstract: *In the present work by employing the Technique for order of preference by similarity to ideal solution (TOPSIS) machining parameters optimization is performed with polycrystalline cubic boron nitride (PCBN) tools while AISI 52100 steel hard turning (HT). Based on the CCD of RSM, 32 experimental runs were performed by varying cutting speed, feed, depth of cut, nose radius, and negative rake angle to identify the optimal level of the process parameters. In this study, the multiple performance characteristics measured are machining force, surface roughness, and workpiece surface temperature. To ascertain the impact of cutting parameters on responses, Analysis of Variance (ANOVA) was deployed. An optimum combination of input process parameters for the multiple performance characteristics should be as follows: speed 200 rpm, feed 0.1 mm/rev, depth of cut 0.8 mm, nose radius 1.2 mm, and negative rake angle 45^o leading to the value of optimum response variables machining force 561.163 N, Surface roughness 0.507µm and workpiece surface temperature 84.38°C.*

Key Words: *Machining force, surface roughness, workpiece surface temperature, TOPSIS, Optimization, ANOVA*

1. INTRODUCTION

The selection of the right process parameters and the achievement of high-performance are important tasks in turning operations. Higher productivity and better output values are achieved through the proper machining parameters optimization in terms of low cutting force, high surface finish, long tool life, and power consumption [1-2].

Umamaheswarrao et al. [3] optimized the machining parameters using TOPSIS while HT of AISI 52100 steel with PCBN inserts. Results revealed that the feed is the most important parameter in controlling the response followed by the depth of cut, negative rake angle, nose radius, and cutting speed. Balasubramaniyan Singaravel and Thangiah Selvaraj [4] used TOPSIS and Analytic Hierarchy Process (AHP) method for determining the optimum machining parameters in turning of EN25 steel. The optimal combination of parameters are cutting speed 179 m/min, feed rate 0.26 mm/rev and depth of cut 1.8 mm with Chemical Vapor Deposition (CVD) coated carbide tool. Bhanu Prakash et al. [5] performed the machining parameters optimization in turning of AISI 1040 steel using AHP and Fuzzy TOPSIS. Arun Kumar Parida and Bharat Chandra Routara [6] carried out the process of the parameters optimization during Glass Fiber Reinforced Plastic (GFRP) composite turning using TOPSIS. Results concluded that the depth of cut has notable influence followed by speed and feed.

Ankita Singh et al. [7] optimized the surface roughness parameters of machined GFRP polyester composites using the TOPSIS and Taguchi method. They observed that the feed rate was the utmost noteworthy factor influencing MPCIs followed by the depth of cut and spindle speed. Maheswararao and Venkata subbaiah [8] optimized the process parameters in Computer Numerical Control (CNC) machining of AA7075 deploying TOPSIS. The results concluded that responses were greatly affected by the feed rate. Sandip Mane and Sanjay Kumar [9] performed the cutting parameters optimization in AISI 4140 steel turning. The results demonstrated that the cutting speed is the significant factor affecting the responses followed by feed and depth of cut.

Umamaheswarrao et al. [10] carried out machining parameters optimization for AISI 52100 steel HT using hybrid GRA-PCA. The results confirmed that speed was the most important factor affecting the responses followed by negative rake angle, feed, depth of cut, and nose radius. Mohapatra and Sahoo [11] revealed that the pulse on time was the greatest important factor in affecting the responses in gear cutting of Inconel 718 by WEDM using TOPSIS. Manivannan and Pradeep Kumar [12] deployed the TOPSIS method of optimization for determining the optimal parameters in micro-EDM of AISI 304 steel. It is concluded that the feed rate and current exerted an utmost influence on the hole quality.

Adalarasan and Shanmuga Sundaram [13] used grey-based TOPSIS for determining the optimum process parameters during FSW of Al/SiC composite. Results revealed that the frictional pressure and upset pressure affecting the quality characteristics. Mohammad Hasan Shojaeefard et al. [14] employed TOPSIS to optimize the process parameters in FSW of AA5083 aluminum alloy.

The results revealed that increasing the rotational speed leads to a significant decrease in the welding force thus increasing the tool lifetime.

Umamaheswarrao et al. [15-16] executed machining parameters optimization while HT of EN31 steel with PCBN tools using TOPSIS.

The results discovered that the negative rake angle is the major parameter in controlling the response followed by feed, depth of cut, cutting speed, and nose radius. TOPSIS was reported to be highly proficient in solving the MCDM problems due to less computational time, simple and easily understandable [17-18]. Hence, the present work employed TOPSIS to optimize machining parameters for AISI 52100 steel hard turning.

2. EXPERIMENTAL DETAILS

In this study, hardened AISI 52100 steel is used as a workpiece material with a hardness of 57 HRC. The workpiece is machined in dry condition on Kirloskar turn master-35 lathe. The required hardness of the workpiece was achieved through the hardening process.

For the current study, five independent variables i.e. cutting speed, feed rate, depth of cut, nose radius and negative rake angle were altered in the range of five levels during the machining operation and the influences of the aforementioned variables on different responses like machining forces, surface roughness and workpiece surface temperature were analyzed. The experimental setup is depicted in Fig. 1. PCBN inserts are presented in Fig. 2. Machining details are presented in Table 1.

Fig. 1 Experimental setup

Fig. 2 PCBN inserts

Table 1. Machining details

Machining condition	Notation	Description
Workpiece material		AISI 52100 steel
Dimensions		500 mm length and 48 mm diameter
Machining length		30 mm
Hardness		57 HRC
Cutting speed (rpm)	ν	200, 400, 600, 800, 1000 rpm
Feed (mm/rev)	f	0.02, 0.04, 0.06, 0.08, 0.1 mm/rev
Depth of cut (mm)	d	0.4, 0.5, 0.6, 0.7, 0.8 mm
Nose radius (mm)	r	0.4, 0.6, 0.8, 1, 1.2 mm
Negative rake angle (°)	α	-5, -15, -25,-35,-45
Cutting inserts		Polycrystalline cubic boron nitride (PCBN)
Tool holder		PSBNR 2525 M12
Tool geometry		CNMG120404, CNMG120406, CNMG120410, CNMG120412
Cutting environment		Dry
Responses	F_M R_a WST	Machining force surface roughness Workpiece surface temperature

3. METHODOLOGY

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS was evolved by Hwang and Yoon based on the concept that the chosen parameter should have the shortest distance from the best solution and the longest distance from the worst solution [19].

In the TOPSIS approach, specific weight is given to output responses in order to rank them. The steps involved in the TOPSIS are given below.

Table 2. Experimental matrix along with results

Expt. No	ν (rpm)	f (mm/rev)	d (mm)	r (mm)	α (°)	F_M (N)	R_a (μm)	WST (°C)
1	400	0.04	0.5	0.6	35	404.735	0.525	57.43
2	800	0.04	0.5	0.6	15	233.475	0.465	74.4
3	400	0.08	0.5	0.6	15	322.117	0.453	65.19
4	800	0.08	0.5	0.6	35	473.03	0.545	77.68
5	400	0.04	0.7	0.6	15	317.493	0.552	71.96
6	800	0.04	0.7	0.6	35	376.384	0.507	82.88
7	400	0.08	0.7	0.6	35	583.032	0.539	70.27
8	800	0.08	0.7	0.6	15	380.407	0.471	65.48
9	400	0.04	0.5	1	15	273.585	0.485	66.3
10	800	0.04	0.5	1	35	425.463	0.401	66.3
11	400	0.08	0.5	1	35	561.163	0.507	84.38
12	800	0.08	0.5	1	15	350.276	0.502	80.11
13	400	0.04	0.7	1	35	443.782	0.508	67.07
14	800	0.04	0.7	1	15	323.621	0.408	80.3
15	400	0.08	0.7	1	15	411.791	0.604	68.76
16	800	0.08	0.7	1	35	523.367	0.498	76.5
17	200	0.06	0.6	0.8	25	430.828	0.559	66.61
18	1000	0.06	0.6	0.8	25	355.441	0.456	82.73
19	600	0.02	0.6	0.8	25	309.595	0.468	70.85
20	600	0.1	0.6	0.8	25	534.481	0.53	74.88
21	600	0.06	0.4	0.8	25	344.431	0.45	71.39
22	600	0.06	0.8	0.8	25	449.219	0.48	74.2
23	600	0.06	0.6	0.4	25	359.396	0.514	67.18
24	600	0.06	0.6	1.2	25	446.225	0.485	76.05
25	600	0.06	0.6	0.8	5	279.954	0.484	70.32
26	600	0.06	0.6	0.8	45	601.276	0.509	73.68
27	600	0.06	0.6	0.8	25	358.525	0.507	68.6
28	600	0.06	0.6	0.8	25	370.743	0.518	74.94
29	600	0.06	0.6	0.8	25	378.525	0.52	71.41
30	600	0.06	0.6	0.8	25	403.976	0.512	66.36
31	600	0.06	0.6	0.8	25	380.24	0.488	76
32	600	0.06	0.6	0.8	25	370.65	0.522	69

STEP 1

In the TOPSIS, the units of all criteria are eliminated and it has been converted into normalized value. The normalized value (r_{ij}) is obtained using equation (1). The normalized performance values and weighted normalized values are shown in Table 3.

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^{2}}} i = 1,2,3\ldots\ldots 32; j = 1,2,3 \tag{1}$$

i = number of alternatives (trials)
j = number of criteria (Output responses)
X_{ij}= represents the actual value of the i^{th} value of j^{th} experimental run.

Table 3. Normalized and weighted normalized Values

Expt. No	Normalized Performance Value			Weighted Normalized Value		
	F_M	Ra	WST	F_M	Ra	WST
1	0.17501	0.18532	0.14482	0.05775	0.06115	0.04779
2	0.10095	0.16414	0.18762	0.03331	0.05416	0.06191
3	0.13928	0.15990	0.16439	0.04596	0.05276	0.05425
4	0.20454	0.19238	0.19589	0.06749	0.06348	0.06464
5	0.13728	0.19485	0.18146	0.04530	0.06430	0.05988
6	0.16275	0.17897	0.20900	0.05370	0.05906	0.06897
7	0.25211	0.19026	0.17720	0.08319	0.06278	0.05847
8	0.16449	0.16626	0.16512	0.05428	0.05486	0.05449
9	0.11830	0.17120	0.16719	0.03903	0.05649	0.05517
10	0.18397	0.14155	0.16719	0.06071	0.04671	0.05517
11	0.24265	0.17897	0.21278	0.08007	0.05906	0.07022
12	0.15146	0.17720	0.20202	0.04998	0.05847	0.06666
13	0.19189	0.17932	0.16913	0.06332	0.05917	0.05581
14	0.13993	0.14402	0.2025	0.04617	0.04752	0.06682
15	0.17806	0.21321	0.17339	0.05876	0.07035	0.05722
16	0.22631	0.17579	0.19291	0.07468	0.05801	0.06366
17	0.18629	0.19732	0.16797	0.06147	0.06511	0.05543
18	0.15369	0.16096	0.20862	0.05072	0.05311	0.0688
19	0.13387	0.16520	0.17866	0.04417	0.05451	0.05896
20	0.23111	0.18708	0.18883	0.07626	0.06173	0.06231
21	0.14893	0.15884	0.18003	0.04914	0.05242	0.05941
22	0.19424	0.16943	0.18711	0.06410	0.05591	0.06174
23	0.15540	0.18144	0.16941	0.05128	0.05987	0.05590
24	0.19295	0.17120	0.19178	0.06367	0.05649	0.06328
25	0.12105	0.17085	0.17733	0.03994	0.05638	0.05851
26	0.26000	0.17967	0.18580	0.08580	0.05929	0.06131
27	0.15503	0.17897	0.17299	0.05116	0.05906	0.05708
28	0.16031	0.18285	0.18898	0.05290	0.06034	0.06236
29	0.16367	0.18355	0.18008	0.05401	0.06057	0.05942
30	0.17468	0.18073	0.16734	0.05764	0.05964	0.05522
31	0.16442	0.17226	0.191656	0.05425	0.05684	0.06324
32	0.16027	0.18426	0.17400	0.05289	0.06080	0.05742

STEP 2

The weighted normalized value (v_{ij}) is computed by multiplying the normalized value by its accompanying weights and is shown in equation (2),

$$v_{ij} = w_j \times r_{ij} \quad i = 1,2,3 \ldots 32; \; j = 1,2,3 \tag{2}$$

Here, equal weightage is given to all the responses [20]. Therefore, $w_j = 0.33$.

Table 4. Positive ideal and Negative ideal solutions

Expt. No	F_M	Ra	WST
1	0.05775	0.06116	0.04779
2	0.03332	0.05417	0.06191
3	0.04597	0.05277	0.05425
4	0.06750	0.06349	0.06464
5	0.04531	0.06430	0.05988
6	0.05371	0.05906	0.06897
7	0.08320	0.06279	0.05848
8	0.05428	0.05487	0.05449
9	0.03904	0.05650	0.05517
10	0.06071	0.04671	0.05517
11	0.08008	0.05906	0.07022
12	0.04998	0.05848	0.06667
13	0.06333	0.05918	0.05581
14	0.04618	0.04753	0.06682
15	0.05876	0.07036	0.05722
16	0.07468	0.05801	0.06366
17	0.06148	0.06512	0.05543
18	0.05072	0.05312	0.06885
19	0.04418	0.05452	0.05896
20	0.07627	0.06174	0.06231
21	0.04915	0.05242	0.05941
22	0.06410	0.05592	0.06175
23	0.05128	0.05988	0.05591
24	0.06367	0.05650	0.06329
25	0.03995	0.05638	0.05852
26	0.08580	0.05929	0.06132
27	0.05116	0.05906	0.05709
28	0.05290	0.06034	0.06236
29	0.05401	0.06057	0.05943
30	0.05765	0.05964	0.05522
31	0.05426	0.05685	0.06325
32	0.05289	0.06081	0.05742
S^+	**0.08580**	**0.07036**	**0.07022**
S^-	**0.03332**	**0.04671**	**0.04779**

STEP 3

Then the PIS (S^+) and NIS (S^-) have been calculated using equation (3),

$$\begin{aligned} s^{+} &= \{(Max(v_{ij}) \mid j\varepsilon J^{*}),\ (Min(v_{ij}) \mid j\varepsilon J^{*})|\ i = 1,2 \cdots 32\} \\ s^{-} &= \{(Min(v_{ij}) \mid j\varepsilon J^{*}),\ (Max(v_{ij}) \mid j\varepsilon J^{*})|\ i = 1,2 \cdots 32\} \end{aligned} \tag{3}$$

where, J is a set of beneficial attributes and J^* is a set of non-beneficial attributes.

The s^+ and s^- values are shown in Table 4.

Table 5. Separation measures, Closeness Coefficient value and rank

Expt. No	D_i^+	D_i^-	C_i	Rank
1	0.037071	0.028386	0.43366	17
2	0.055549	0.015973	0.223327	31
3	0.046382	0.015439	0.249737	29
4	0.020328	0.041639	0.671957	6
5	0.04223	0.024483	0.36699	25
6	0.034045	0.031889	0.483648	12
7	0.014212	0.053483	0.790056	3
8	0.03848	0.023471	0.378861	23
9	0.05104	0.013529	0.209529	32
10	0.037616	0.02837	0.429939	18
11	0.012667	0.053308	**0.808008**	1
12	0.037903	0.027793	0.423058	19
13	0.028942	0.033469	0.536271	11
14	0.045854	0.022986	0.333906	26
15	0.030001	0.035993	0.545401	9
16	0.017862	0.045723	0.719078	5
17	0.028944	0.034498	0.543776	10
18	0.039111	0.028058	0.417719	20
19	0.045936	0.017425	0.275013	28
20	0.015088	0.047764	0.759943	4
21	0.042213	0.02045	0.326346	27
22	0.027408	0.03503	0.561035	8
23	0.038809	0.023705	0.379201	22
24	0.027014	0.03546	0.567599	7
25	0.049342	0.015893	0.243627	30
26	0.014204	0.055637	0.796621	2
27	0.03873	0.023606	0.378693	24
28	0.035274	0.02796	0.442169	15
29	0.034965	0.027494	0.440186	16
30	0.033651	0.028536	0.458872	13
31	0.035015	0.02793	0.443723	14
32	0.03658	0.025971	0.415201	21

STEP 4

The separation of each alternative from PIS ($S^{+)}$ and NIS (S^-) is found as per equation (4) and equation (5),

$$D_i^+ = \sqrt{\sum_{i=1}^{32} \left(v_{ij} - s_j^+\right)^2} \quad i = 1,2 \cdots 32 \tag{4}$$

$$D_i^- = \sqrt{\sum_{i=1}^{32} \left(v_{ij} - s_j^-\right)^2} \quad j = 1,2,3 \tag{5}$$

STEP 5

The closeness coefficient value of each alternative (C_i) is calculated as shown in equation (6), The closeness coefficient values are shown in Table 5.

$$C_i = \frac{D_i^-}{D_i^- + D_i^+} \tag{6}$$

4. RESULTS AND DISCUSSIONS

From the main effects plot (shown in Fig. 3) the optimum parameters were recognized at speed 200 rpm, feed 0.1 mm/rev, depth of cut 0.8 mm, nose radius 1.2 mm, and negative rake angle 45º. Exp. No Vs closeness coefficient is depicted in Fig. 4.

Table 6. Mean response table for Closeness Coefficient

Level	Factor				
	Cutting Speed	Feed	Depth of cut	Nose radius	Negative rake angle
Level 1	**0.574851**	0.23095	0.291998	0.381743	0.19651
2	0.506351	0.347397	0.411098	0.440754	0.302155
3	0.451339	0.44319	0.455091	0.448840	0.442075
4	0.414622	0.573577	0.509876	0.480220	0.618819
5	0.321778	**0.779767**	**0.552099**	**0.549875**	**0.829824**
Max-Min	0.253073	0.548817	0.260101	0.168132	0.633314
Rank	**4**	**2**	**3**	**5**	**1**

The higher value of comparative closeness value indicates better performance. From Table 5, it is evident that the experiment number 11 accomplished the highest value of closeness coefficient amongst the 32 experiments and the optimum condition to achieve the multiple performance characteristics (cutting speed = 200 rpm, feed rate = 0.1 mm/rev, depth of cut = 0.8 mm, nose radius = 1.2 mm and negative rake angle = 45º)

From Table 5, it is evident that experiment number 11 was the better performer. The order of the experimental run obtained by TOPSIS was given by 11-26-7-20-16-4-24-22-15-17-13-6-30-31-28-29-1-10-12-18-32-23-8-27-5-14-21-19-3-25-29.

In the response table (Table 6) negative rake angle allocated a rank 1 which means it is the most noteworthy parameter in controlling the response followed by feed, depth of cut, cutting speed and nose radius.

From the ANOVA analysis, it is clear that negative rake angle contribution is maximum (50.55%) afterward feed (29.58%), depth of cut (6.01%), cutting speed (5.38%), and nose radius (1.48%) as depicted in Table 7.

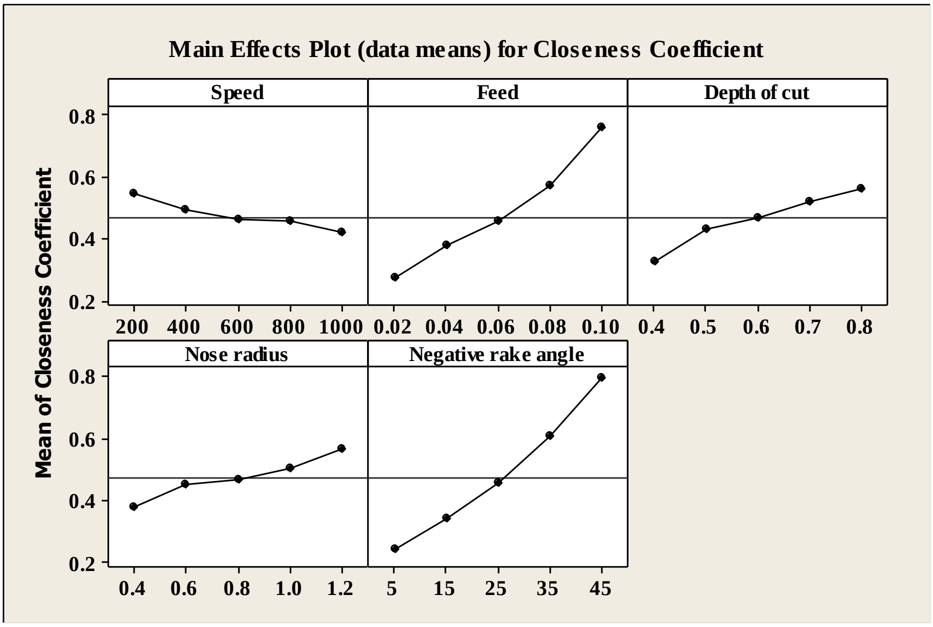

Fig. 3 Main effects plot for closeness coefficient

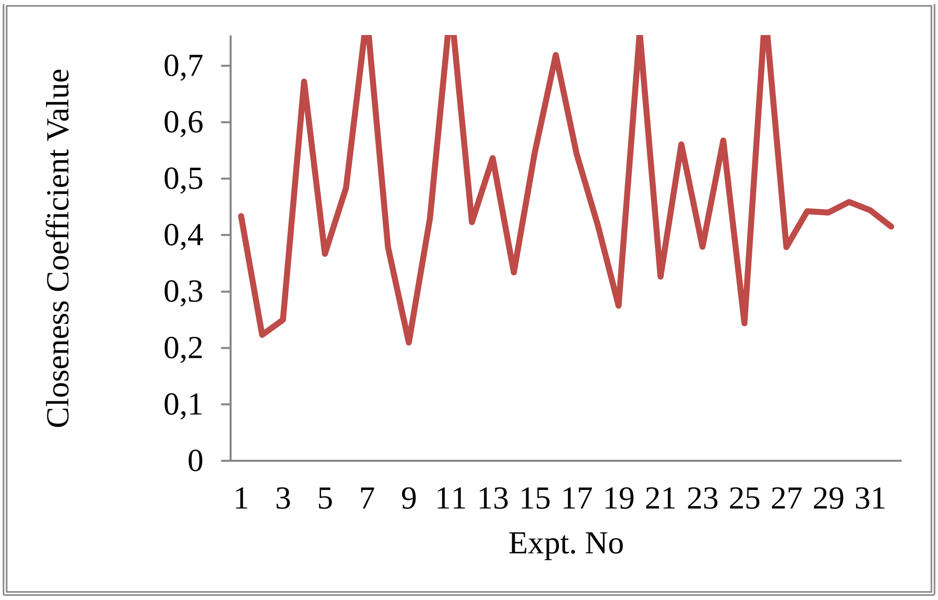

Fig. 4 Expt. No Vs closeness coefficient

The closeness coefficient for the obtained optimum combination of parameters was 1.39765 appraised from Eq. 7 and was 72.97% greater than the maximum closeness coefficient corresponding to rank 1 in Table 5.

Hence the values obtained were optimal.

$$\gamma = \gamma_m + \sum_{i=1}^{q} (\overline{\gamma_j} - \gamma_m) \tag{7}$$

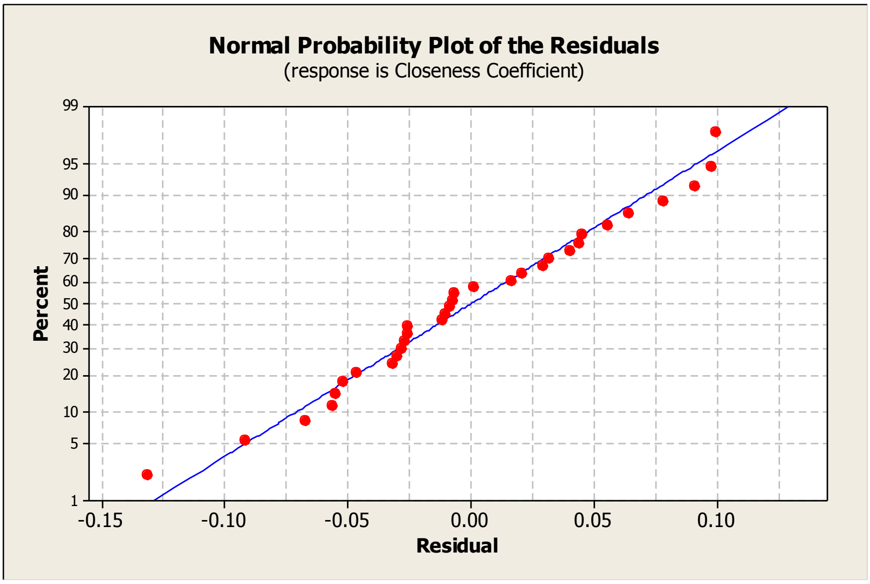

Fig. 5 Normal probability plot for residuals

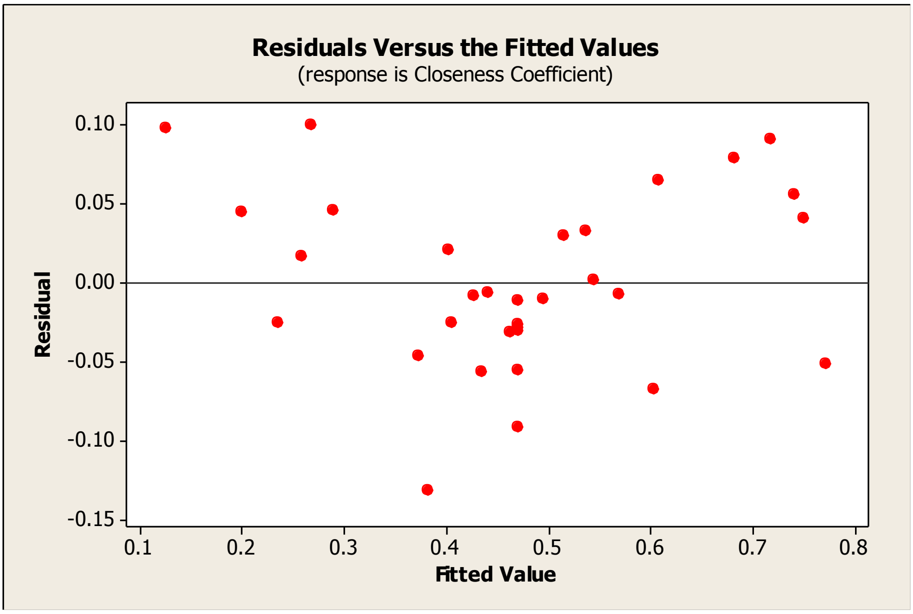

Fig. 6 Residuals versus the fitted values

The normal probability plot is presented in Fig. 5. The errors are distributed normally because the residuals fall on a straight line [21]. The residuals versus the fitted values are depicted in Fig. 6. The residuals are dispersed in both positive and negative direction and they do not show any apparent pattern. This denotes that the model is satisfactory and there is no reason to suspect any violation of the independence [22]. From Fig. 7 it is apparent that the closeness coefficient increases with an increase in feed, depth of cut, nose radius, and negative rake angle. The highest closeness coefficient is observed at low speed, high feed, high depth of cut, high nose radius, and upper limits of negative rake angle.

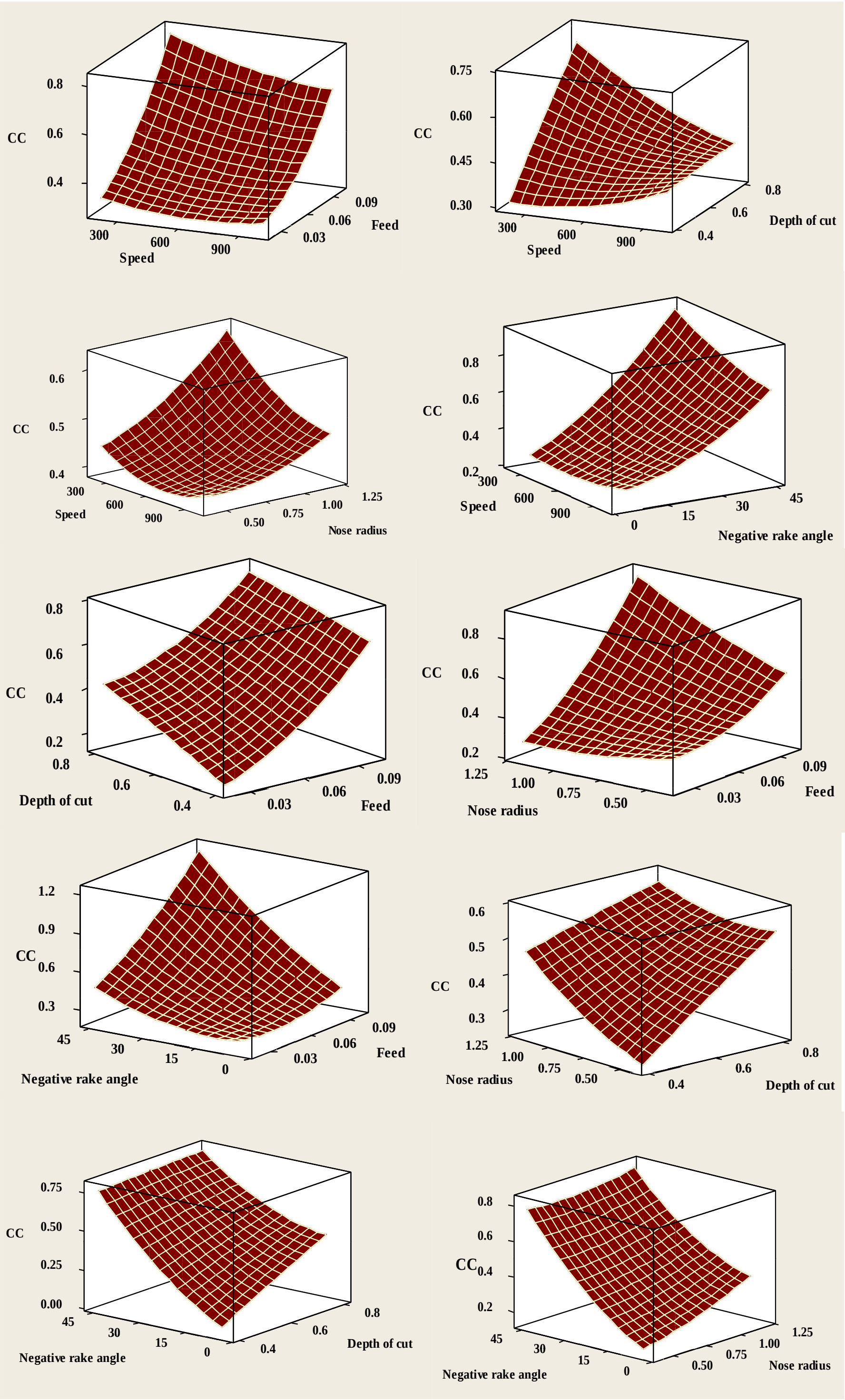

Fig. 7 Response surface plots

Table 7. ANOVA for closeness coefficient

Source	Sum of Squares	DF	Mean Square	F-value	p-value	% Contribution
ν	0.0641	1	0.0641	41.22	< 0.0001	5.386
f	0.3521	1	0.3521	226.55	< 0.0001	29.588
d	0.0716	1	0.0716	46.03	< 0.0001	6.0168
r	0.0177	1	0.0177	11.40	0.0062	1.4873
α	0.6016	1	0.6016	387.09	< 0.0001	50.554
ν*f	0.0001	1	0.0001	0.0925	0.7667	0.0084
ν*d	0.0128	1	0.0128	8.22	0.0153	1.0756
ν*r	9.894E-06	1	9.894E-06	0.0064	0.9378	0.00083
ν*α	0.0031	1	0.0031	1.99	0.1864	0.26050
f*d	0.0024	1	0.0024	1.55	0.2392	0.20168
f*r	0.0028	1	0.0028	1.82	0.2049	0.23529
f*α	0.0129	1	0.0129	8.32	0.0148	1.08403
d*r	0.0026	1	0.0026	1.70	0.2192	0.21848
d*α	0.0118	1	0.0118	7.57	0.0188	0.99159
r*α	0.0012	1	0.0012	0.7485	0.4054	0.10084
ν^{2}	0.0003	1	0.0003	0.2106	0.6552	0.02521
f^{2}	0.0091	1	0.0091	5.85	0.0341	0.76470
d^{2}	0.0003	1	0.0003	0.1964	0.6662	0.02521
r^{2}	0.0017	1	0.0017	1.12	0.3120	0.14285
α^{2}	0.0112	1	0.0112	7.22	0.0212	0.94117
Residual	0.0171	11	0.0016			1.43697
Lack of Fit	0.0111	6	0.0019	1.56	0.3216	0.93277
Pure Error	0.0060	5	0.0012			0.50420
Cor Total	1.19	31				

5. CONCLUSIONS

In the current study, the optimal settings of the cutting parameters were found while turning of AISI 52100 hardened steel utilizing PCBN inserts and the following conclusions are drawn:

i) The negative rake angle is the most important parameter in controlling the response followed by the feed, depth of cut, cutting speed and nose radius.

ii) From the ANOVA, negative rake angle (50.55%) has major effect subsequently feed (29.58%), depth of cut (6.01%), cutting speed (5.38%) and nose radius (1.48%)

iii) It is clear from the results of TOPSIS that the experiment number 11 has the highest closeness coefficient value. Thus the optimal parametric combinations are at speed 200 rpm, feed 0.1 mm/rev, depth of cut 0.8 mm, nose radius 1.2 mm, and negative rake angle 45^{o}.

iv) From the values of the closeness coefficient, the machining parameters best combination can be arranged in the order 11-26-7-20-16-4-24-22-15-17-13-6-30-31-28-29-1-10-12-18-32-23-8-27-5-14-21-19-3-25-29, respectively.

v) An improvement of 72.97% of the predicted weighted closeness coefficient confirms the optimality of the obtained results.

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