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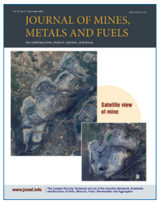

Experimental Analysis of Machining Performances of CNC Milling Using AlTiN Coated Tungsten Carbide Tool (WC)

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Abstract

Higher accuracy and precision are highly demandable in modern industry through computer-aided manufacturing technology. The paper deals with the parametric analysis for helix angle(°), radial depth of cut (mm), axial depth of cut (mm) and cutting speed(m/min) as well as the second-order mathematical modelling for Surface Roughness (SR) as surface texture (R_a), Tool Wear Rate (TWR) and machining rate as a form of Material Removal Rate (MRR) have been carried out. Analysis of Variances (ANOVA) is performed during helical profile cutting on cast iron based on modelling. Multi-response, as well as single objective optimization, has been done for finding the best process parameters setting for maximum MRR and minimum TWR and SR using desirability function analysis during profile cutting by advanced CNC milling. It is found that surface finish accuracy is increased with better surface quality and lower tool wear found with maximized MRR using AlTiN (aluminium titanium nitride) coated Tungsten carbide Tool (WC).

Keywords: *Accuracy, CNC Milling,* ***Desirability Function Analysis,*** *FG 200, MRR,* ***Optimization,*** *SR, TWR*

1.0 Introduction

Advanced computer numerical control milling is an essential machine tool to utilize in modern industrial field for helical profile cutting on brittle materials like cast iron by the leading of CNC programming using aluminium titanium nitride coated tungsten carbide tool. CNC is an integrated part of computer-aided manufacturing science and technology. The use of brittle materials is increasing day by day and it is difficult to cut helical profiles on them. Upadhyay, *et al.,*[1] reduced surface irregularities by vibration in all directions. Moriwaki[2] used a pattern recognition process to identify the state of CNC turning. Dhabale, *et al.,*[3] analyzed parametric effects on SR and MRR using computer numerical control turning. K Palani Kumar, *et al.,*[4] propounded effects of Feed Rate (FR), Cutting Speed (SP) on Surface Roughness (SR) for SiC using RSM. Kathamore, *et al.,*[5] reviewed CNC milling during the machining of aluminum alloy by the Taguchi method. Ranganath, *et al.,*[6] optimized surface roughness during the turning operation of aluminium. K Siva *et al.,*[7–9] propagated CNC milling of aluminium alloy to minimize surface roughness using the Taguchi technique. Vardhan, *et al.,*[10] showed that MRR was increased by escalating Cutting Speed (CS), Feed Rate (FR) as well as DOC for the milling of P20 steel. Tsao[11] reduced the flank wear and surface roughness up to 0.24 μm. Liao and Lin[12] showed that cutting speeds varied from 200-500m/min and played a vital role in the machining of P20 steel by CNC milling. Nadaf, *et al.,*[13] obtained the least surface roughness 0.0857μm for CNC milling of MS. Nooruddin, *et al.,*[14] found that the MRR is maximum at cutting speed

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230m/min, 0.40mm/revolution feed rate and DOC 1.5 mm for dry turning of grey cast iron. Sokovic, *et al.*,[15] analyzed the good and bad effects of cutting fluid during machining. Hameed, *et al.*,[16] used advanced aluminium as a job specimen for CNC turning by a tungsten carbide tool to fabricate tiny components. Hricova, *et al.*,[17] showed that primary surface texture increased with the decrease of the cutting speed (CP) during the milling of Aluminium alloy. Aslantas, *et al.*,[18] analyzed that due to higher Spindle Speeds (SP) rapidly TWR occurred that increased Surface Roughness (SR).

Most of the researchers used HSS, boron-carbide, carbide tools or ceramics and stainless steel tools during CNC milling operations and they applied their thoughts to aluminium or steel, very few researchers did their works on cast iron for only findings MRR but did not fulfil others machining performance characteristics by CNC milling and not applied their results for fabrication of miniature products or in helical profile cut or not in helical gear cut on cast iron. To fulfil the research gap in CNC milling, the purpose of the present research has been defined and carried out. Desirability function analysis has been performed and the findings can be applied to fabricate helical gear cut or profile cut that can encourage the engineer, researcher and scientist to focus their targets.

2.0 Experimental Set-Up and Planning

Figure 1 shows the vertical CNC milling machine which is used to run the experiments step by step. The range of parameters is selected based on the trial and error method for better accuracy and precision. Feed is kept fixed at 0.1mm/s during profile cutting by vertical advanced milling. The face-centred Design of Experiments (DOE) is chosen by the Response Surface Methodology (RSM) as desirability function analysis[19–22]. Table 1 shows the ranges and levels with the code of parameters for experimentation.

Figure 1. Image of Vertical CNC Milling Machine.

Table 1. Range of parameters

Process Parameters (Variables)	Range		
	-1	0	+1
Helix angle (HA) (°)(x1)	10	15	20
Radial depth of cut (RDOC) (mm)(x2)	0.20	0.30	0.40
Axial depth of cut (ADOC)(mm)(x3)	0.5	.75	1
Cutting speed (CS) (m/min)(x4)	60	70	80

3.0 Results Analysis and Discussion

To fulfil the target of the research, each and every set of experiments have been conducted three times to find the accurate results for that parametric combination and their average value of test results has been taken for result discussion. Table 2 shows the parametric combination as well as the test results.

3.1 Adequacy Test of Developed Modeling

For maximization of tool life, TWR is minimized and to increase the Machining Rate (MR), MRR has been maximized also for better surface quality, SR is minimized during vertical CNC milling of FG200 grey cast iron.

Second-order mathematical models have been formed with the correlation and interaction effects of process parameters[23–26] with machining criteria during helical profile cutting on cast iron by CNC milling. Models are expressed as Eq. 1, 2 and 3 for MRR, TWR and SR.

Max_MRR(x) = Y(MRR) = 49.2750 +0.0686*x(1)+ 0.2174 *x(2)- 0.8446*x(3)+ 1.1327 *x(4)-0.0003*(x(1))^2-0.2578*(x(2))^2+0.4362*(x(3))^2+0.1692*(x(4))^2+0.2425*x(1)*x(2)-0.0019*x(1)*x(3)+0.3765*x(1)*x(4)+0.0051*x(2)*x(3) +0.0147*x(2)*x(4) -0.4214*x(3)*x(4); Equ. *(1)*

Min_TWR(x) = Y(TWR) = 0.039200 +0.000078*x(1)+ 0.000244*x(2) + 0.000861*x(3)+ 0.001156*x(4)+0.000000*(x(1))^2-0.000300*(x(2))^2+0.000450*(x(3))^2+0.000200*(x(4))^2+0.000219*x(1)*x(2)-0.000019*x(1)*x(3)+0.000356*x(1)*x(4)-0.000006*x(2)*x(3) -0.000006*x(2)*x(4) -0.000444*x(3)*x(4); Equ. *(2)*

Table 2. Experimental plan and test results

Run Order	Helix angle(^{0})	Radial Depth of cut(mm)	Axial depth of cut(mm)	Cutting Speed (m/min)	MRR (gm/s)	TWR (mg/hr)	SR (μm)
1	10	0.2	0.50	60	47.345	0.0370	1.0450
2	20	0.2	0.50	60	46.990	0.0369	1.0459
3	10	0.4	0.50	60	47.170	0.0371	1.0481
4	20	0.4	0.50	60	47.450	0.0374	1.0484
5	10	0.2	1.00	60	49.891	0.0398	1.0490
6	20	0.2	1.00	60	48.987	0.0389	1.0479
7	10	0.4	1.00	60	50.612	0.0406	1.0940
8	20	0.4	1.00	60	49.564	0.0395	1.0820
9	10	0.2	0.50	80	50.232	0.0402	1.1090
10	20	0.2	0.50	80	49.865	0.0398	1.1140
11	10	0.4	0.50	80	50.015	0.0400	1.0690
12	20	0.4	0.50	80	51.457	0.0414	1.0810
13	10	0.2	1.00	80	50.785	0.0407	1.1517
14	20	0.2	1.00	80	51.456	0.0414	1.1514
15	10	0.4	1.00	80	50.217	0.0402	1.1520
16	20	0.4	1.00	80	52.468	0.0424	1.1521
17	10	0.3	0.75	70	49.368	0.0393	1.0499
18	20	0.3	0.75	70	48.633	0.0386	1.0581
19	15	0.2	0.75	70	48.487	0.0384	1.0524
20	15	0.4	0.75	70	48.999	0.0389	1.0583
21	15	0.3	0.50	70	48.564	0.0385	1.0370
22	15	0.3	1.00	70	50.310	0.0403	1.0750
23	15	0.3	0.75	60	48.219	0.0382	1.0280
24	15	0.3	0.75	80	50.121	0.0401	1.0900
25	15	0.3	0.75	70	48.698	0.0386	1.0445
26	15	0.3	0.75	70	49.931	0.0399	1.0464
27	15	0.3	0.75	70	49.365	0.0393	1.0491
28	15	0.3	0.75	70	49.876	0.0396	1.0486
29	15	0.3	0.75	70	49.354	0.0393	1.0478
30	15	0.3	0.75	70	49.971	0.0399	1.0489
31	15	0.3	0.75	70	49.375	0.0393	1.0487

Min_SR(x) = Y(SR) = 1.04658+0.00073*x(1)+ 0.00103*x(2)+0.01987*x(3)+ 0.03233*x(4) +0.00873*(x(1))^2+0.01008*(x(2))^2+0.01073*(x(3))^2+0.01373*(x(4))^2- 0.00026*x(1)*x(2) -0.00197*x(1)*x(3)+0.00179*x(1)*x(4) +0.00922*x(2)*x(3) -0.00979*x(2)*x(4) + 0.00929 *x(3)*x(4); Equ. *(3)*

Analyses of variances have been analyzed to predict the adequacy of test models, using P value a F-ratio and R^2 as well as Adj.R^2. Fitness of the developed 2nd order non-linear mathematical models of MRR, TWR and SR have been done comparing with the standard P value, F ratio value and standard confidence level of (95%) with the DOF for the lack of fit along with R^2 as well as Adj. R^2 value which has been found by the regression analysis. Desirability function analysis has been performed to adequacy test for ANOVA prediction. ANOVA analysis for MRR, TWR and SR represents the fitness of the data as well as the developed models. The R^2 and Adj.R^2 for MRR, TWR and SR are (93.81%, 90.76%), (94.91%, 93.81%) and (99.71%, 99.46%) respectively. Table 3 shows the ANOVA table of Adj.SS and Adj.MSS for MRR, TWR and SR during CNC milling of FG200 cast iron. Table 4 shows the ANOVA table of the F ratio test and P value for MRR, TWR and SR. From Table 3 and 4, it is clear the adequacy and fitness of developed non-linear models because for 10 DOF of lack of fit as well as p-value is within the range of standard value.

3.2 Parametric Analysis on MRR, TWR and SR

Figures 2 (a)-(d), 3 (a)-(d) and 4 (a)-(d) show the parametric effects like HA, CS, RDOC and ADOC on MRR, TWR and SR respectively. From Figure 2 (a) it is observed that if the axial depth of the cut, as well as the radial depth of the cut, enlarges, MRR become higher because MR enlighten and from Figure 2 (b) it is said that if the helix angle is increased MRR decreases and if cutting speed is increased, MRR increases because the higher axial force has been tendered on the machining zone and rate of machining increases but not only that if helix angle is increased, cutting edge of milling cutter involvement in the machining zone will decrease, so as material removal decrease. It is found from Figure 2 (c) that CS as well as ADOC both influences directly on MRR and become higher at a higher level of CS and ADOC when RDOC is kept fixed at 0.3mm and the helix angle is at 15° at constant. From Figure 2 (d) it is found that at 0.4 mm RDOC tends to reduce MRR at axial depth 0.75mm and CS 70m/min and then increase of helix angle, MRR decreases.

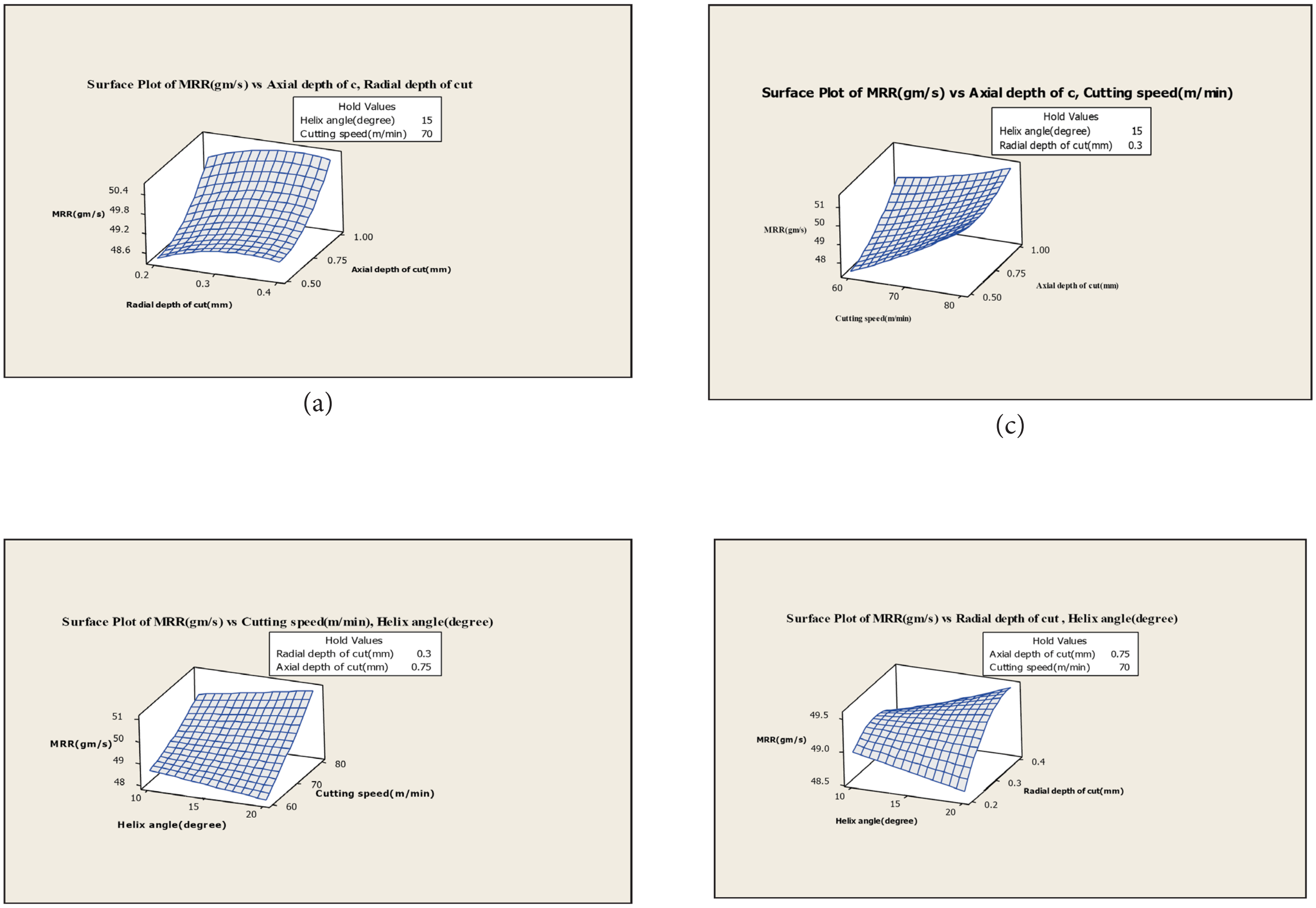
From Figure 3 (a) it is found that if ADOC, as well as RDOC, increases, TWR increases because axial, as well as Radial Force (RF) acts accordingly, so tool wear occurs due to the engagement of higher Axial Force (AF) mainly and from Figure 3 (b) it is observed that if helix angle is augmented tool wear rate becomes higher due to contraction as well boost of direct action between tool and job, as a result, more tool defects occur and if CS increases, TWR increases because higher AF acts on the machining zone. It is observed from Figure 3 (c) that CS and ADOC both have direct effects on TWR and increase at a higher level of CS as well as at higher ADOC, then others parameters are held on. From Figure 3 (d) it is observed that at 0.3 mm RDOC and 0.75mm ADOC and 70m/min CS, the tool wear rate become higher and after that TWR become smaller at 10° Helix Angle (HA), TWR is lower, when others parameters kept fixed at a moderate level.

Table 3. Analysis of Variance (ANOVA) of Adj.SS and MSS for MRR, TWR and SR

Source	DF	Adj.SS MRR	Adj.SS TWR	Adj.SS SR	Adj.MSS MRR	Adj.MSS TWR	Adj.MSS SR
Regression	14	44.161	0.000046	0.041697	3.1544	0.000003	0.002978
Linear	4	36.8676	0.000039	0.025949	9.2169	0.000010	0.006487
Square	4	1.2397	0.000001	0.011357	0.3099	0000000	0.002839
Interaction	6	6.0538	0.000006	0.004391	1.0090	0.000001	0.000732
Lack-of-Fit	10	3.2244	0.000003	0.000104	0.3224	000000	0.000010
Pure Error	06	1.2466	0.000001	0.000017	0.2078	000000	0.000003
Total	30						

Table 4. Analysis of Variance (ANOVA) of F ratio and P value for MRR, TWR and SR

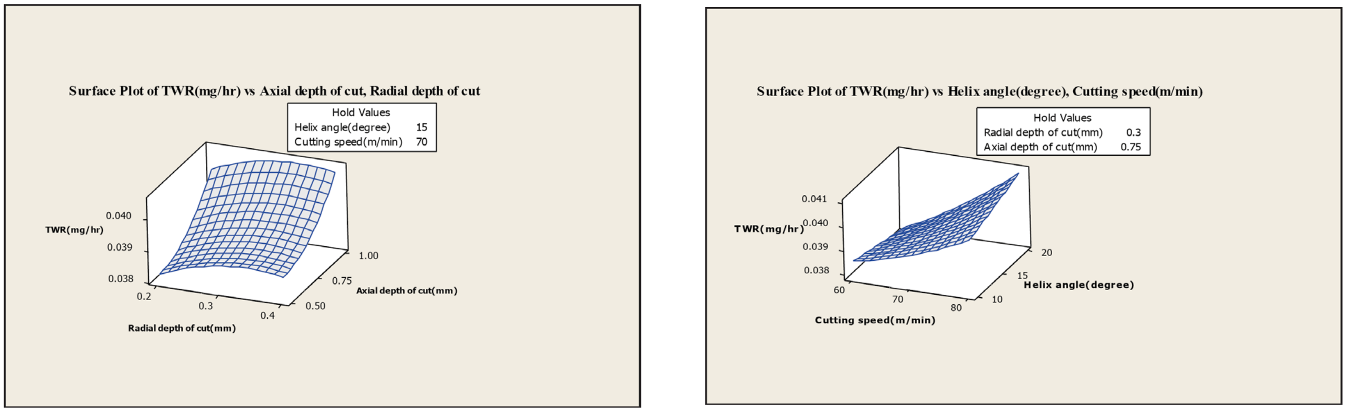
Source	DF	F (ratio) for MRR	F (ratio) for TWR	F (ratio) for SR	P (value) MRR	P (value) TWR	P (value) SR
Regression	14	11.29	11.80	392.18	0000	0000	0000
Linear	4	32.98	34.71	854.22	0000	0000	0000
Square	4	64.64	1.21	373.88	0.386	0.345	0000
Interaction	6	1.11	3.57	96.37	0.019	0.019	0000
Lack-of-Fit	10	1.55	1.61	3.65	0.305	0.290	0.063
Pure Error	06						
Total	30						



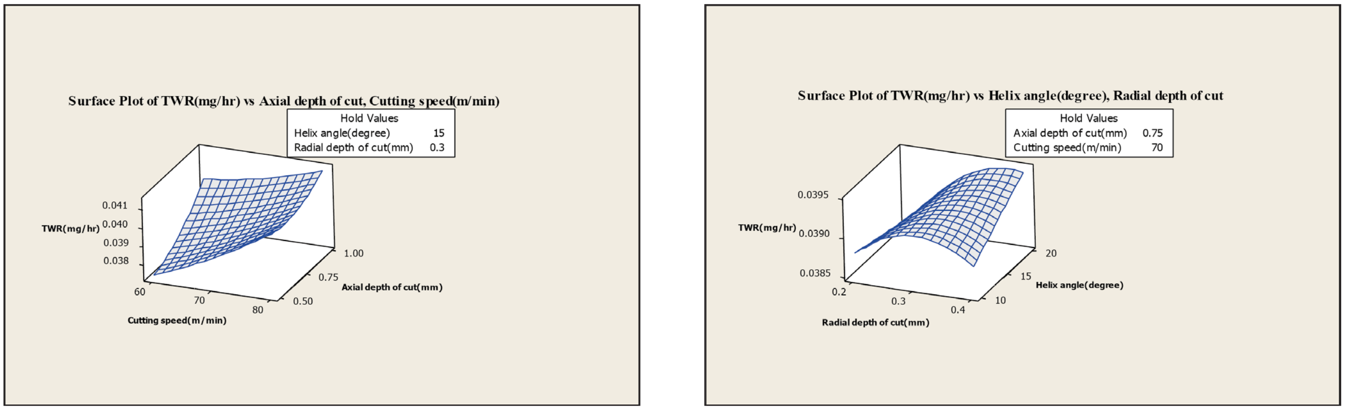
(a) (c)

(b) (d)

Figures 2. (**a**) Effect of RDOC and ADOC on MRR, (**b**) Effect of HA and CS on MRR, (**c**) Effect of CS and ADOC on MRR, (d) Effect of HA and RDOC on MRR.



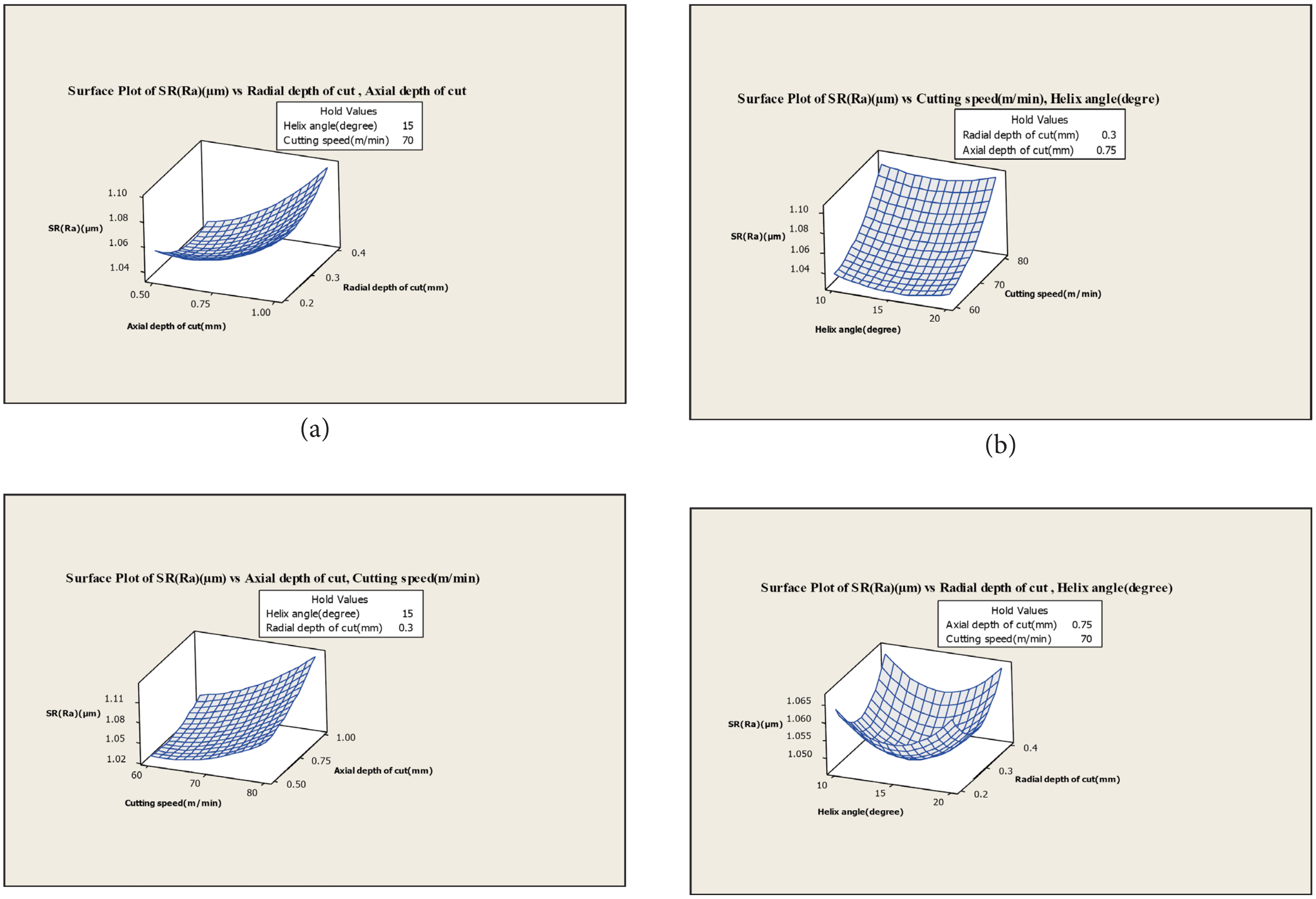
(a) (b)



(c)

(d)

Figures 3. **(a)** Effect of RDOC and ADOC on TWR, **(b)** Effect of HA and CS on TWR, (c) Effect of CS and ADOC on TWR, **(d)** Effect of HA and RDOC on TWR.



(a)

(b)

(c)

(d)

Figures 4. **(a)** Effect of RDOC and ADOC on SR **(R_a)**, **(b)** Effect of HA and CS on SR **(R_a)**, (c) Effect of CS and ADOC on SR **(R_a)** (d) Effect of HA and RDOC on SR **(R_a).**

From Figure 4 (a), it is propounded that if ADOC or RDOC increases, tool wear becomes higher than influencing on cutting zone, so the surface texture becomes irregular and surface roughness amplifies. As an aluminium titanium nitride coated tungsten carbide tool is used, surface irregularity becomes less and improves surface quality and increases tool life. If more tool wear occurs surface texture becomes irregular. From Figure 4 (b), it is found that at 15° HA surface roughness becomes lower if RDOC is 0.3mm and ADOC is 0.75mm and CS is 60m/min. A good surface finish is achieved. It is observed from Figure 4 (c), that if CS and axial depth of cut both increase during CNC milling surface roughness increases if the helix angle is kept at 15° and the radial depth of cut is 0.3mm. It is observed that when two variables are varied, another two are kept fixed. From Figure 4 (d), it is observed that after 0.3 mm RDOC, SR becomes higher and at 15° HA, a good quality surface creates, then CS is fixed at 70m/min and ADOC is 0.75mm and after 15° of HA, surface roughness increases.

3.3 Multi-criteria Optimization for Maximum MRR and Minimum TWR and SR

Figures 5, 6 and 7 show the single objective optimization graphical plot for max. MRR and min. TWR and SR respectively. Figure 8 shows the multi-criteria optimization of machining characteristics of CNC milling during profile cutting on FG200 grey cast iron using response surface methodology-based desirability function analysis. From all optimization plots, it is observed that the desirability is near about 1 which indicates the acceptance of desired parametric combinations for the responses. It is found that MRR is optimized at the parametric combination of 20° helix angles, 0.39 mm RDOC, 1mm ADOC and 80m/min CS and at desirability 0.99; MRR is 52.1024 g/s. It is found that TWR is minimum at the parametric combination of 20° helix angles, 0.20 mm RDOC, 0.50 mm axial depth of cut and 60m/min cutting speed and at desirability 1; TWR is 0.0346 mg/hr. SR is minimum at 15° helix angles, 0.26 mm RDOC, 0.67mm ADOC and 60m/min CS and at desirability 1; SR is found at 1.0242 **µm**. For multi-response optimization max.MRR is 49.3680g/s, min. TWR is 0.0393mg/hr and SR is 1.0361µm at 13.630 helix angle, 0.22 mm RDOC, 0.94mm axial depth of cut and 60m/min cutting speed for CNC milling of FG200 grey cast iron.

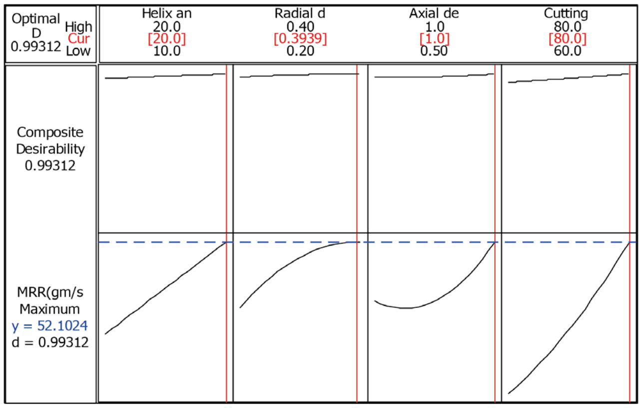


Figure 5. Single Response-optimization for maximum MRR.

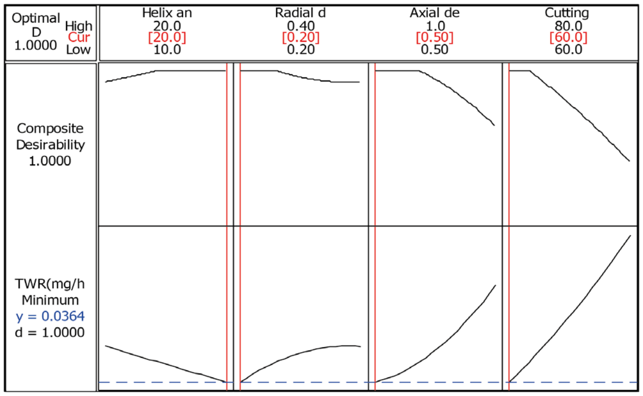


Figure 6. Single Response-optimization for minimum TWR.

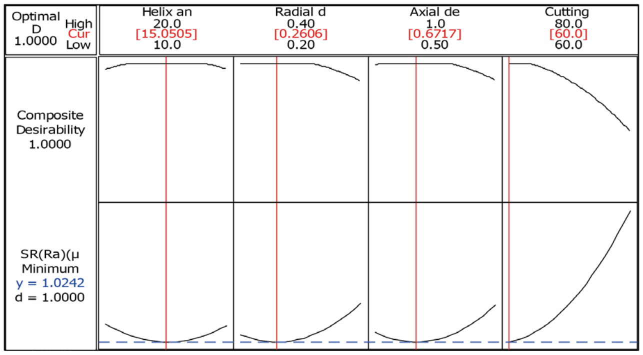


Figure 7. Single Response-optimization for minimum SR.

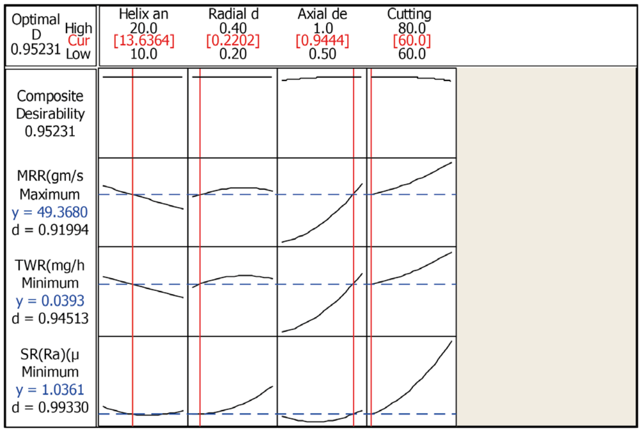


Figure 8. Multi-objective-Response for Maximum MRR, minimum TWR and SR.

4.0 Conclusions

By the proper investigations as well as analysis of graphical representation and developed models of present research it is concluded that:

- MRR increases by increasing the CS, ADOC, RDOC and by decreasing the helix angle.
- TWR and SR are increased by increasing CS, ADOC, and RDOC but at 10 to 15° helix angle tool wear rate reduces and the quality surface is produced during CNC milling of FG200 cast iron.
- It is observed that developed mathematical models are justified by the adequacy test of ANOVA analysis during profile cutting by CNC milling.
- Multi-characteristics responses optimized (MRR is 49.3680g/s, TWR is 0.0393mg/hr and SR 1.0361μm) at 13.630 helix angle, 0.22 mm radial depth of cut, 0.94mm axial depth of cut and 60m/min cutting speed for CNC milling of FG200 grey cast iron.
- Using aluminium titanium nitride coated tungsten carbide (WC) tool CNC milling performances improved with good quality surface and maximized tool life, as tool wear rate decreases drastically.

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