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Optimization of Resultant Cutting Force in CNC Turning Process for Hard (62-64 HRC) AISI M2

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Abstract: In this research work the influence of machining parameters including cutting speed, feed rate and depth of cut on a resultant cutting force in a dry turning environment for hard AISI M2 are investigated using the Taguchi method and analysis of variance (ANOVA).A three level, three parameter design of experiment, the L27 orthogonal array using Minitab 17 software, the single to noise (S/N) ratio are employed to optimize the resultant cutting force in the turning of hard AISI M2 by taking nose radius of the PCBN insert (Kennametal) of 0.8mm.The analysis of variance (ANOVA) is applied to investigate the contribution of each machining parameters while CNC turning of AISI M2 material.The results are verified by taking confirmation experiments.The present study indicates that cutting speed is the most influencing factor for resultant cutting force while turning hard (62-64HRC) AISI M2 material.

Keywords: CNC turning, Resultant Cutting Force, Taguchi method, Hard AISI M2, PCBN insert

I. INTRODUCTION

The CNC turning process is common machining process. It is found in near about in all manufacturing industries. After vibration response parameter optimization in CNC turning next important parameter is cutting force. This factor is also equally responsible for tool wear and tool life. Especially in the hard turning the study of cutting for forces is very important to get the minimum surface roughness.

Li, B. et al. [1], presented a analytical study based on the unequal shear zone model to study machining predictive theory. The cutting force can be predicted only by the work-piece material properties and cutting condition. In shear zone, the material constitutive relationship is described by Johnson–Cook model, and the material characteristics such as strain rate sensitivity, strain hardening, and thermal softening are considered. They assumed the chip formation within the primary shear zone and governing flow equation is established by the introducing a piecewise power law distribution assumption of the shear strain rate. They calculated cutting force for different cutting condition in computing the flow stress, the strain, strain rate, and temperature effects are taken into consideration. Jadhav J. S. and Jadhav B. R. [2], studied effect of cutting parameters on cutting force (Fc) & feed force in turning Process. They conducted experiment on precision centre LATHE machine and influence of cutting parameter has been studied with use of analysis of variance technique (ANOVA) which is based on adjustable approach. They considered three level of cutting parameter. The result shows that feed rate has significant effect on cutting force surface roughness. They show that cutting speed not having much more influence on the cutting force and surface roughness. According to this study Optimum surface roughness can be achieved by selecting relatively higher values of speed (>65.37m/min), higher values of depth of cut (>0.75mm), and relatively lower values of feed rate (<0.10mm/rev).Ghani, J. A. et al. [3], studied the online tool wear using low cost technique and user friendly GUI. For this, they use low cost sensor. Due to that the system is able to detect and analyze signals relating to the deflection of the tool holder from the cutting force, and the corresponding estimation of wear is displayed on the computer screen. In experimental process they used two-channel strain gauge at tool holder to measure deflections in both tangential direction and feed direction. MATLAB software is used as the platform software to develop a user-friendly graphical user interface (GUI) for online monitoring purposes. Cus, F. and Zuperl, U. et al. [4], developed a real time monitoring system that can detect tool breakage in real time by using a combination of neural decision system and ANFIS tool wear estimator. They used ANFIS method to extract the features of tool states from cutting force signals. Force signals contain the most useful information for determining the tool condition. The ANFIS method uses the relationship between flank wear and the resultant cutting force to estimate tool wear. They uses speed, feed, depth of cutting, time and cutting forces were used as input parameters and flank wear width and tool state were output parameters and number of experiment performed. Cutting forces were used as input parameters and flank wear width and tool state were output parameters. For measuring force they use the piezoelectric dynamometer and data acquisition system.

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Simultaneously flank wear at the cutting edge was monitored by using a tool maker's microscope. So that the developed monitoring system machining process can be on-line monitored and stopped for tool change based on a pre-set tool-wear limit.

On the strength of the evaluation of work done by former investigators, it is found that a huge amount of research work has been carried out for modeling, simulation and parametric optimization of surface properties of the material in turning operation.The problems related to tool life, tool wear and cutting forces are also addressed to.However no work is found for optimizing the surface characteristics for hard (62-64 HRC) AISI M2 material using PCBN 0.8 mm nose radius insert in the dry turning environment.

This investigation demonstrates details of Taguchi optimization technique to optimize the resultant cutting force. The main objective of present study is to find out process parameter's set which will give minimum resultant cutting force value while turning hard AISI M2 on a CNC machine.

II. EXPERIMENT DESIGN PHASE

The design of experiment is an offline method to inspect quality of any manufacturing process. There are a number of methods to design experiments such as factorial design, response surface design, mixture design, and Taguchi design. Taguchi method is the oldest method of optimization and is industrial accepted method.It is powerful tool to design high-quality system.It follows systematic, simple and efficient approach to optimize designs for performance, quality and cost.[8]

Table1. Control Factors with Levels

Levels	Control Parameters		
	Cutting Speed (mm/min)	Feed Rate (mm/rev)	Depth of Cut (mm)
L1	100	0.1	0.4
L2	140	0.15	0.5
L3	180	0.2	0.6

Taguchi method uses Signal-to-Noise ratios to measure the performance characteristics. In the present research, work experiment is designed by Taguchi technique, which uses an orthogonal array to investigate the entire parametric space with a limited number of experimental trials. The three machining parameters considered in this study are cutting speed, feed rate, and depth of cut. The nose radius 0.8mm is taken constantly in this investigation because it gives better performance as per the previous study was done on this material processing [5].All machining parameters are set at three different levels (see Table 1).The selection of particular orthogonal matrix is done with help of MINITAB 17 software.In this software for three parameters available orthogonal arrays are L9, L18, and L27.In the present study, the L27 orthogonal array is selected to find more accurate optimum value of response characteristic.In this research work, the interactions between factors are considered.The response variables chosen for the present investigation is resultant cutting force. The smaller is the better quality characteristic is employed for resultant cutting force.

Condition of S/N ratio for resultant cutting force is smaller is better

$$S/N = -10 \times log(\Sigma(Y^2)/n)) \quad (1)$$

Where, S/N-Signal to Noise Ratio, Yi – i^{th} observed value of the response, n - Number of observations in a trial, Y - Average of observed responses values. After finalizing control factors and their levels, the design of orthogonal matrix is prepared using MINITAB 17 statistical software which is shown in below.

III. EXPERIMENTATION CONDUCTION PHASE

The three cylindrical hard (62-64 HRC) specimens of AISI M2 are selected for experimental trials.The specimen size is taken as Ø59×350mm.The chemical composition of AISI M2 specimen material were C-0.86/0.96, Cr-3.8/4.5, Mo-4.9/5.5, W-6.0/6.75, V-1.7/2.2[7] and the properties of AISI M2 are density-8.028×10-3g/mm3, melting point-46800, hardness-62-65 HRC, compressive yield strength-3250 Mpa, Poisson's ratio-0.27-0.30, elastic modulus-190-210 Gpa [7].The application of AISI M2 material involves manufacturing of twist drills, reamers, taps and cold forming tools such as extrusion rams and dies and also to prepare plastic molds with elevated wear resistance and screw[7].In present work, the cutting tool used for turning AISI M2 hard specimen is rectangular shape PCBN CNMG160408 insert which is shown in Figure 2.The clearance angle of the insert is zero.The inscribed circle size is 9.5mm and thickness is 5mm.The tool holder used during experimentation is PCLNR 2525M12 which is shown in Figure3.The properties of cutting tool material are high melting point, high thermal conductivity, low coefficient of thermal expansion.

Table 2. Experiment Design and Conduction with L27 OA and S/N Ratio calculation

Expt. No.	Cutting Speed	Feed Rate	Depth of Cut	Cutting Force Fx	Cutting Force Fy	Cutting Force Fz	Cutting Force Fr	S/N Ratio (dB)
1	100	0.1	0.4	88.25	107.87	88.25	284.37	-49.08
2	100	0.1	0.5	127.48	127.48	117.67	372.63	-51.43
3	100	0.1	0.6	137.29	166.71	137.29	441.29	-52.89
4	100	0.15	0.4	98.06	156.9	39.22	294.18	-49.37
5	100	0.15	0.5	117.67	284.39	176.59	578.65	-55.25
6	100	0.15	0.6	166.71	333.42	186.32	686.45	-56.73
7	100	0.2	0.4	107.87	382.45	205.93	696.25	-56.86
8	100	0.2	0.5	147.09	323.61	362.84	833.54	-58.42
9	100	0.2	0.6	127.48	107.87	68.64	303.99	-49.66
10	140	0.1	0.4	78.45	88.25	29.41	196.11	-45.85
11	140	0.1	0.5	107.87	98.06	78.45	284.38	-49.08
12	140	0.1	0.6	137.29	88.25	107.87	333.41	-50.46
13	140	0.15	0.4	68.64	88.25	58.83	215.72	-46.68
14	140	0.15	0.5	107.87	88.25	78.45	274.57	-48.77
15	140	0.15	0.6	137.29	98.06	88.25	323.60	-50.20
16	140	0.2	0.4	58.83	78.45	49.03	186.31	-45.40
17	140	0.2	0.5	88.25	78.45	107.87	274.57	-48.77
18	140	0.2	0.6	156.9	137.29	196.13	490.32	-53.81
19	180	0.1	0.4	68.64	68.64	39.22	176.50	-44.93
20	180	0.1	0.5	88.25	58.83	58.83	205.91	-46.27
21	180	0.1	0.6	117.67	58.83	68.64	245.14	-47.79
22	180	0.15	0.4	58.83	68.64	49.03	176.50	-44.93
23	180	0.15	0.5	98.06	58.83	78.45	235.34	-47.43
24	180	0.15	0.6	117.67	58.83	68.64	245.14	-47.79
25	180	0.2	0.4	58.83	68.64	58.83	186.30	-45.40
26	180	0.2	0.5	98.06	68.64	78.45	245.15	-47.79
27	180	0.2	0.6	117.67	58.83	78.45	254.28	-48.11

The CNC machine used in this experimentation is ACE make and model simple turn 5075 with Siemens 802controller. The CNC lathe has a maximum spindle speed of 2000 rpm and a power of 380 v/4.5v.The CNC lathe has 250 mm maximum turning diameter and 700 mm maximum turning length.[6] The all experimental trials are conducted without coolant and as per sequence of design of orthogonal matrix.

Figure 4. Experimental Unit (VIIT, Pune)

Figure 5. Digital Tool Dynamometer Showing Optimum Responses in Fx, Fy, and Fz Direction in Kg at cutting speed 180mm/min, feed rate 0.1mm ,and depth of cut 0.

Table3. Specification of Digital Tool Dynamometer [6]

Sr. No.	Particulars	Details
1	Tool holder	(3 comp) with 1" tool holder (PCLNR 2525M12)
2	Display	LCD
3	Reading	Peak hold facility
4	Port	RS232

The turning process is done for three specimens as per design of orthogonal array.The slot of 2.5 mm is done on specimens. After machining, the resultant cutting force is measured in the feed direction using Tool Dynamometer (see Figure 5).A photograph of the resultant cutting force measurement setup is shown in Figure 5.The set of three readings is taken on each slot to measure cutting force (Fr)in three. Directions such as Fx, Fy, and Fz. After getting set of three readings, resultant cutting force is calculated by Equation 2 (see Table 2).

$$Fr = \sqrt{(Fx)}^2 + \sqrt{(Fy)}^2 + \sqrt{(Fz)}^2 \quad (2)$$

IV. OPTIMIZATION, ANALYSIS AND MODELING FOR RESULTANT CUTTING FORCE

A. *Optimum Predicted Resultant Cutting Force*

The optimum value of resultant cutting force can be calculated by manually hand calculation as well as using MINITAB 17 software.

Let F'= average results for 27 runs of resultant cutting force value = 334.837 N

$$F' = \frac{\sum_{i=1}^{27} F_i}{27} \quad (3)$$

$$Response_{optimum} = F' + (A_{n1} - F') + (B_{n2} - F') + (C_{n3} - F') + (D_{n4} - F') \text{ [Ross,1988]} \quad (4)$$

Where A_{n1}, B_{n2}, C_{n3} and D_{n4} are corresponding mean values of optimum points indicated in S/N graph.

= 334.837 + (218.9 - 334.837) + (282.2 - 334.837) + (268.0 - 334.837)

Optimum resultant cutting force (Fr) by manual hand calculation =100 N

Now,calculating optimum resultant cutting force by using MINITAB17 software.

So,optimum resultant cutting force (Fr) predicted by MINITAB 17 software = 173.643 N

From the above calculation, the conclusion can be drawn that there is a minor error (73.64N) between manually and software predicted optimum resultant cutting force value and therefore it is proved that the optimum resultant cutting force is accurately calculated.

Table 3. Response Table for Means

Level	Cutting Speed	Feed Rate	Depth of Cut
1	499.0(A1)	282.2(B1)	268.0(C1)
2	286.6(A2)	336.7(B2)	367.2(C2)
3	218.9(A3)	385.6(B3)	369.3(C3)
Delta	280.1	103.4	101.3
Rank	1	2	3

Table 4. Response Table for Signal to Noise Ratios (Smaller is Better)

Level	Cutting Speed	Feed Rate	Depth of Cut
1	-53.30	-48.64	-47.61
2	-48.78	-49.68	-50.36
3	-46.72	-50.47	-50.83
Delta	6.58	1.83	3.21
Rank	1	3	2

Table 3 and Table 4 shows that level such as A3(180 mm/min),B1(0.1mm/rev),and C1(0.4mm) is optimum level of process parameter which gives optimum resultant cutting force and resultant cutting force is more influenced by the cutting speed (rank 1) and then depth of cut (rank 2).

B. Analysis of Variance for Resultant Cutting Force

The purpose of the analysis of variance (ANOVA) is to investigate which parameter significantly affects the response factor most. The method of manually ANOVA calculation is given below.

Table 5. Application of ANOVA for S/N ratios

Source	DOF	Seq.SS	Adj.SS	Adj.MS	F	P
Cutting Speed	2	203.92	203.92	101.960	12.97	0.003
Feed Rate	2	15.11	15.11	7.553	0.96	0.423
Depth of Cut	2	54.24	54.24	27.122	3.45	0.083
Cutting Speed* Feed Rate	4	10.38	10.38	2.594	0.33	0.850
Cutting Speed * Depth of Cut	4	20.21	20.21	5.053	0.64	0.647
Feed Rate * Depth of Cut	4	10.59	10.59	2.647	0.34	0.846
Residual Error	8	62.87	62.87	7.859		
Total	26	377.32				
S = 2.803 R-Sq. = 83.3% R-Sq.(adj.) = 45.8%						

From Table 5, it can be concluded that cutting speed is the most significant factors which affect the resultant cutting force.

C. Regression Analysis for Resultant Cutting Force

The correlation between the process parameters and response factor such as resultant cutting force are obtained using regression analysis technique. The regression equation is as follows:

Resultant Cutting Force (N) = 412 - 4.39(Cutting Speed) + 2064(Feed Rate) + 4939(Depth of Cut) (5)

Weighted analysis using weights in Ra (Average) is as follows:

Table 6. Predictor's Coefficient Value

Predictor	Coefficient	Sec. Coefficient	T- value	P- value
Constant	412.0	207.2	1.99	0.058
Cutting Speed	-4.3881	0.7944	-5.52	0.000
Feed Rate	2063.9	604.8	3.41	0.002
Depth of Cut	492.7	320.4	1.54	0.137
S = 2467.00 R-Sq. = 63.1% R-Sq.(adj.) = 58.6%				

Table7. Analysis of Variance for Regression

Source	DOF	SS	MS	F- value	P- value
Regression	3	2596581334	86552711	14.22	0.000
Regression Error	25	152151662	6086066		
Total	28	411809796			

V. RESULTS AND DISCUSSIONS

A. Effect of Cutting Speed on Resultant Cutting Force

Figure 7 illustrates the evolution of resultant cutting force according to the cutting speed. Figure 7 shows that the resultant cutting force initially decreases with increase in cutting speed up to 140 mm/min and then increases with increase in cutting speed up to 180 mm/min.Figure 6 shows that at 140 mm/min, the resultant cutting force is at an optimum level means we will get the better surface finish at 140 mm/min.The cutting speed is a most influencing factor for the resultant cutting force value and the second one is a depth of cut.

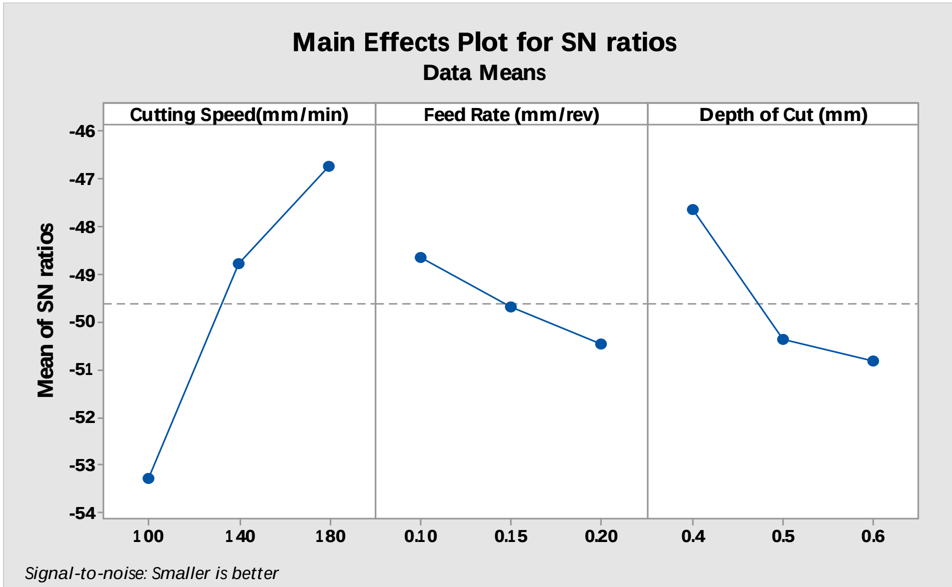

Figure6. Main Effects Plot for SN Ratios

B. Effect of Feed Rate on Resultant Cutting Force

Figure 7 illustrates the evolution of resultant cutting force according to the feed rate. Figure 7 shows that the resultant cutting force initially increases slowly with increase in feed rate up to 0.15 mm/rev and then decreases sharply with increase in feed rate up to 0.2 mm/rev. Figure 6 shows that at 0.2 mm/rev, the resultant cutting force is at an optimum level means we will get better finishing at 0.2mm/rev feed rate.

C. Effect of Depth of Cut on Resultant Cutting Force

Figure 7 shows the evolution of resultant cutting force according to the depth of cut. Figure 7 shows that the resultant cutting force initially increases slightly with the increase in the depth of cut up to 0.5 mm and then increases sharply with increase in depth of cut up to 0.6 mm.Figure 6 shows that at 0.4 mm, the resultant cutting force is at an optimum level means we will get better finishing at 0.4 mm depth of cut.

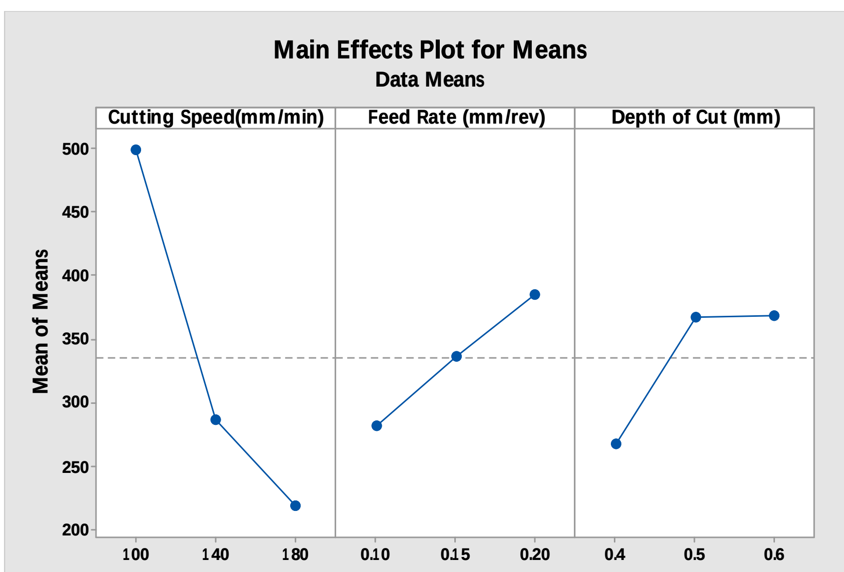

Figure7. Main Effects Plot for Means

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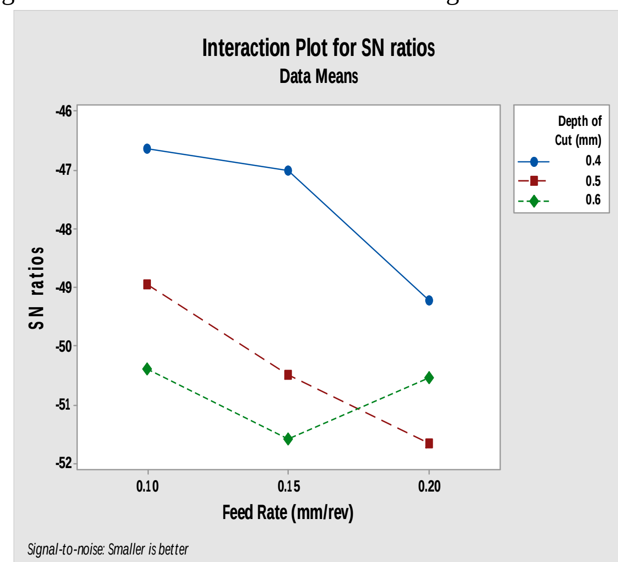
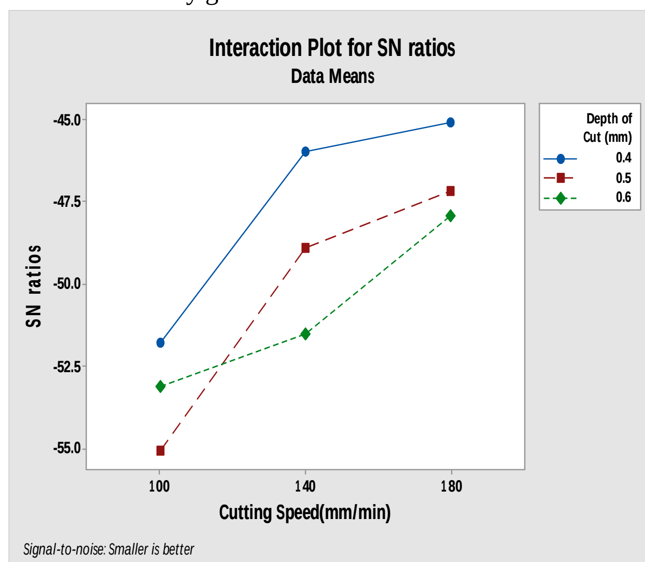
D. Interaction Plots for Signal to Noise Ratios of Resultant Cutting Force

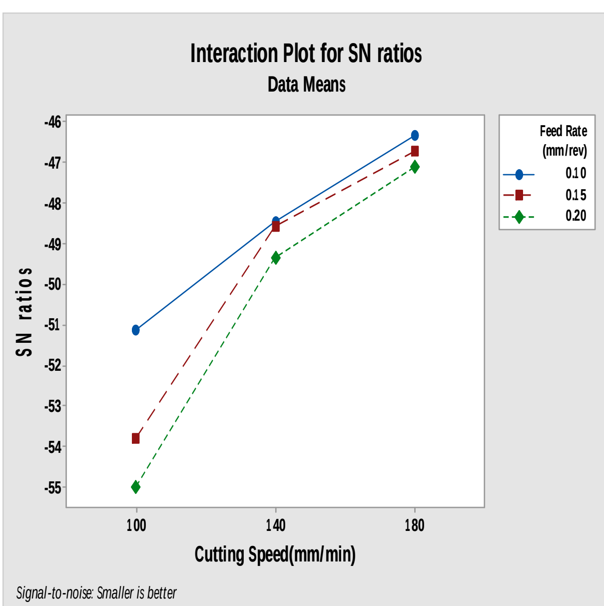
Figure 8 shows the plots for the signal to noise ratios of resultant cutting force with normal probability plot. In Figure 8 (a) the green dotted line shows 0.20 mm/rev feed rate, the blue continuous line shows 0.10 mm/rev feed rate, and the red dotted line shows 0.15 mm/rev feed rate.The feed rate 0.20 mm/rev gives the maximum value of the signal to noise ratio at cutting speed of 140 mm/min means interaction of these two factors gives optimum resultant cutting force value. In Figure 8 (b) the green dotted line shows 0.6 mm depth of cut, the blue continuous line shows 0.10 mm depth of cut and red dotted line shows 0.5 mm depth of cut.The depth of cut of 0.4 mm gives the maximum value of the signal to noise ratio at cutting speed of 140 mm/min means interaction of these two factors gives optimum resultant cutting force value.In Figure 8 (c) the green dotted line shows 0.6 mm depth of cut, the blue continuous line shows 0.10 mm depth of cut and the red dotted line shows 0.5 mm depth of cut.The depth of cut of 0.4 mm gives the maximum value of the signal to noise ratio at a feed rate of 0.20 mm/rev means interaction of these two factors gives optimum resultant cutting force value.Figure 8 (d) shows the probability plot for the response which is the signal to noise ratio.It shows that all signal to noise ratio values follows the straight line means our model is statically good.



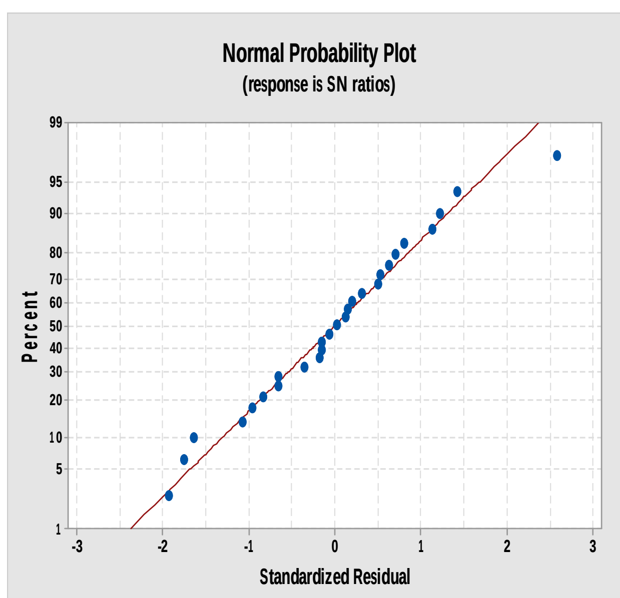
(a)



(b)



(c)



(d)

Figure 8. Interaction Plots for Single to Noise Ratios of Resultant Cutting Force with the Normal Probability Plot

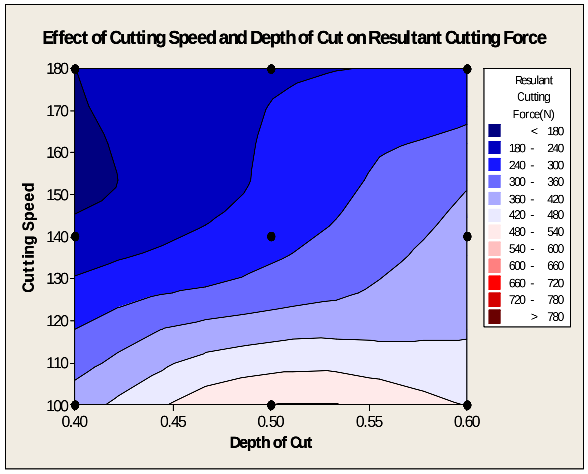


Figure 9. (a) Counter Plot to Study Influence of Cutting Speed and Depth of Cut on a Resultant Cutting Force

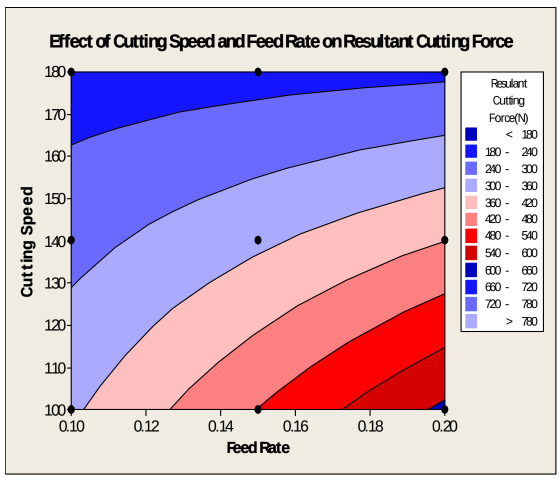


Figure 9. (b) Counter Plot to Study Influence of Cutting Speed and Feed Rate on a Resultant Cutting Force

Figure 9 (a) shows the counter plot to investigate the influence of cutting speed and depth of cut on a resultant cutting force. It shows that the resultant cutting force value is minimum in the area acquired by cutting speed range from 140 mm/min to 160 mm/min and depth of cut range from 0.40 mm to 0.50 mm and Figure 9 (b) shows that shows the counter plot to investigate the influence of cutting speed and feed rate on a resultant cutting force. It shows that the resultant cutting force value is minimum in the area acquired by cutting speed range from 140 mm/min to 170 mm/min and feed range from 0.14mm/rev to 0.18 mm/rev.

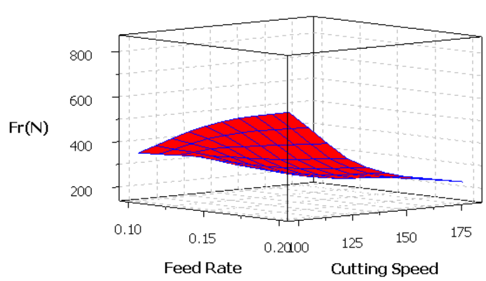


Figure 9. (a) Surface Plot to Study Influence of Cutting Speed and Feed Rate on a Resultant Cutting Force

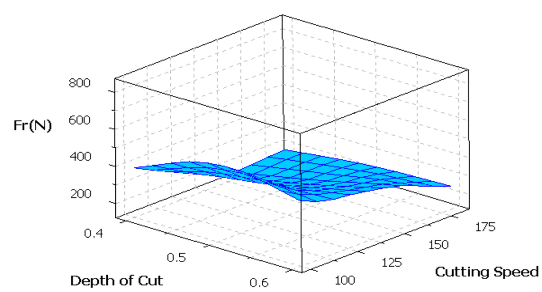


Figure 9. (b) Surface Plot to Study Influence of Cutting Speed and Depth of Cut on a Resultant Cutting Force

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VI. VALIDATION OF RESULT

In order to validate the results obtained six confirmation experiments are conducted for the response characteristic at optimal levels of the process variables.The average values of the characteristics are obtained and compared with the predicted values.The results are given in Table 8. The value of resultant cutting force obtained through confirmation experiments are within the 95% of CI of respective response characteristic.It is to be pointed out that these optimal values are within the specified range of process variables

Table 8. Confirmation Tests for Resultant Cutting Force (Fr)

Sr.No.	Optimum Value of Parameters	Optimum Level of Parameters	Optimum Predicted Value of Resultant Cutting Force(N)	Optimum Experimental Value of Resultant Cutting Force (N)	Error (N)
1.	Cutting Speed	A3	173.643	282.50	108.85
2.	= 180 mm/min	B1	173.643	281.21	107.56
3.	Feed Rate	C1	173.643	278.32	104.67
4.	= 0.1 mm/rev		173.643	280.44	106.79
5.	Depth of Cut		173.643	284.31	110.66
6.	= 0.4 mm		173.643	282.23	108.58
		Average	173.643	281.5017	107.85

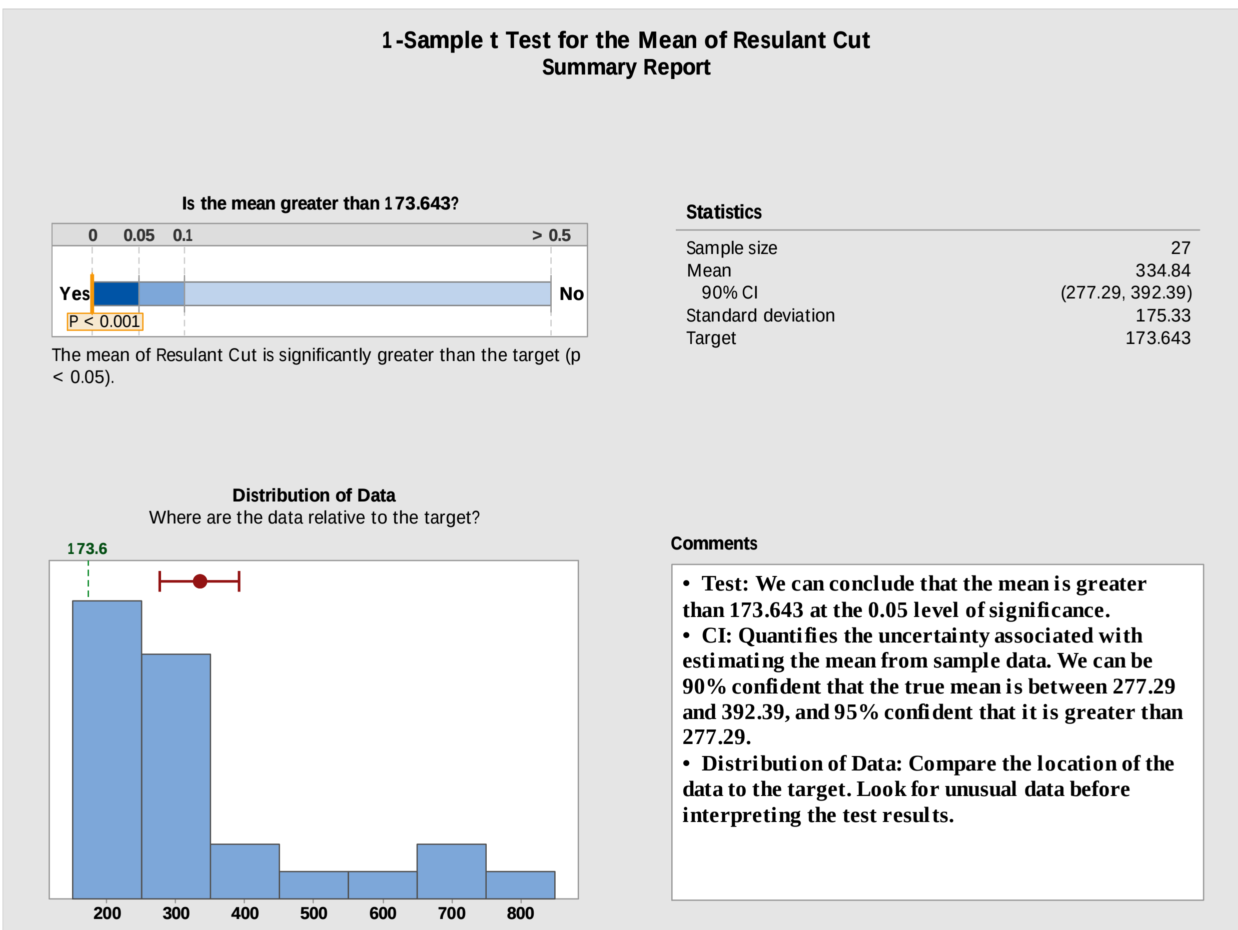

Figure 10. 1-Sample t Test for Mean of Resultant Cutting Force

Figure 10 shows the diagnosis test performs with help of MINITAB17 software to find confidence interval and it shows that the value of resultant cutting force obtained through confirmation experiments are within the 95% of CI of respective response characteristic.i.e.$277.29 \leq 281.50 \leq 392.39$

VII. CONCLUSIONS

The turning tests are conducted on the hard AISI M2 specimens using the PCBN insert with 0.8 mm nose radius.The influences of cutting speed, feed rate, and depth of cut are investigated by Taguchi and ANOVA on the resultant cutting force. Based on the results obtained, the following conclusions are drawn

A. It is observed that the cutting speed and depth of cut are most significant parameters those affect the resultant cutting force most as per the analysis of variance (ANOVA) while hard turning of AISI M2 on a CNC machine.
B. The optimum level of process parameters is A3, B1, and C1 with a 0.8 mm nose radius of the PCBN insert (i.e. cutting speed= 180 mm/min, feed rate= 0.1 mm/rev, and depth of cut = 0.4 mm) for the hard turning of AISI M2 on a CNC machine to minimize the resultant cutting force.
C. The optimum value of resultant cutting force at optimum level of machining parameters is 281.50 (Experimental Value of Resultant Cutting Force).

VIII. ACKNOWLEDGEMENTS

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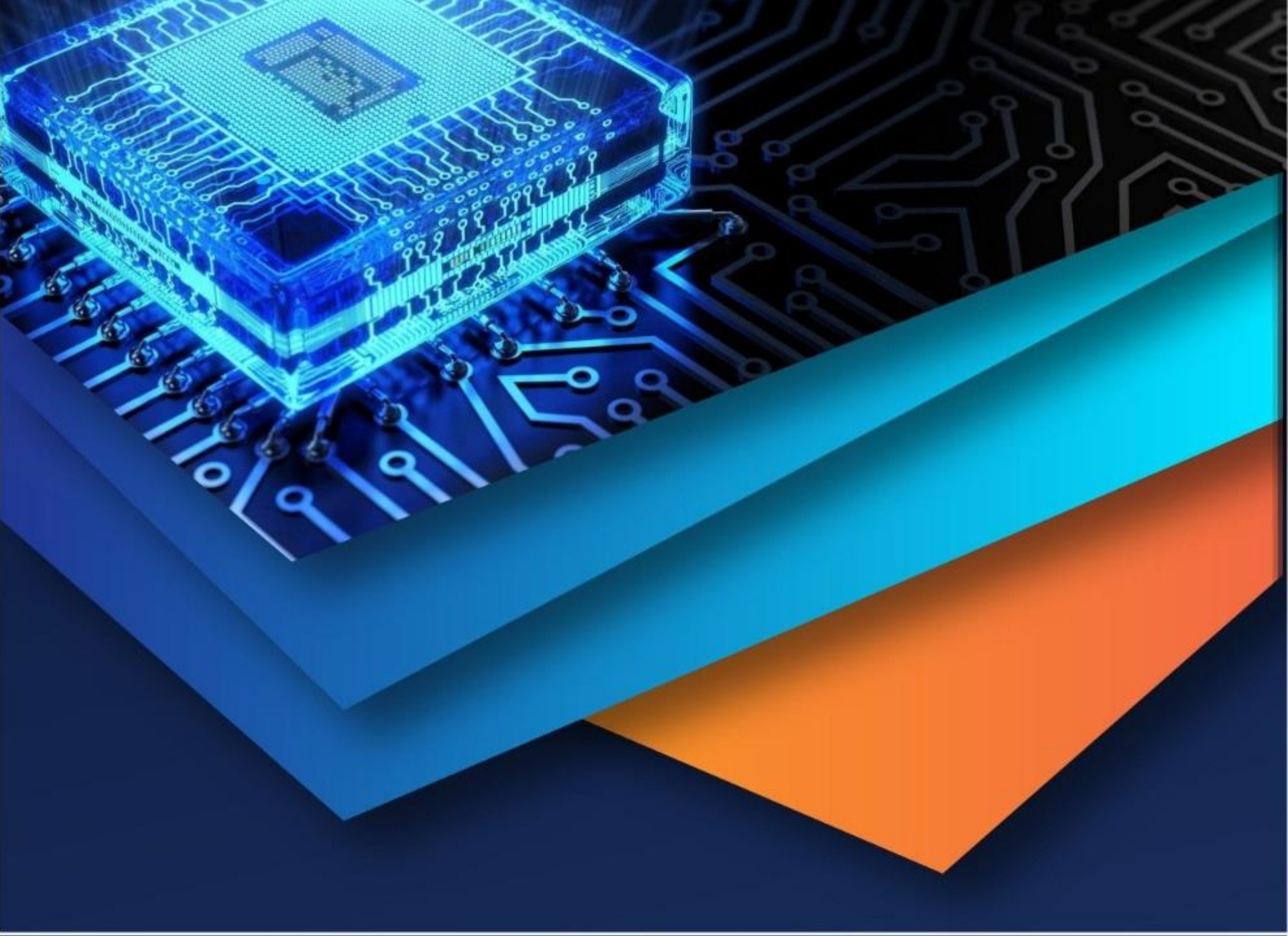

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