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Analysis of Cutting Force Component in Hard Turning Process by Application of RSM (Response Surface Methodology) Technique

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Abstract—*In this study, measurement of responses i.e. cutting forces (F_X, F_Y, F_Z) in hard turning process of AISI D2 steel (55 HRC hardness) with Mitsubishi CBN (cubic boron nitride) were carried out. The parameter selected for experimentation were cutting speed (m/min), feed rate (mm/rev) and depth of cut (mm). The effect of these parameters on the responses were determined with RSM (Response surface methodology) technique.*
Machining experiment were conducted with central composite design of experiment consisting of 20 experimental run. The cutting forces were measured by Kistler dynamometer.
ANOVA (Analysis of Variance) applied to results obtained to determine which parameter or interaction of parameter had significant effect on each response. Full quadratic model was fitted for each of the responses. The main effect plot and interaction effect plot shows, how does the responses changes when input parameters were subject to changes. Counter plot and surface plots were showing the general trend of response and help to select particular value of input parameter for desired response.
Depth of cut had the most significant influence on all the three force components with 38.12%, 40.09%, 38.78% contribution towards F_X, F_Y and F_Z respectively. Feed rate was significant parameter for F_X and F_Y component with contribution of 23.25%, 16.53% respectively. For the optimization of all the three forces, input parameters are found out.

1. INTRODUCTION

Hard turning processes can be defined as turning metal parts that are already hardened, into finished components. The advantage of using finish hard turning includes reduced machining time and complexity required to manufacture metal parts. In addition to the ability-to-machine using defined cutting edges, hard turning has other advantages such as coolant can be eliminated, higher MRR (metal removal rates) (as compared to grinding while finishing) could be achieved. Also, part geometrics (complex) are manufactured. This process differs from conventional turning in that relatively low cutting speed, feeds and depth of cut are normally used.

2. LITERATURE REVIEW

Hamdi Aouici et al. [1] studied the effects of cutting speed, feed rate, workpiece hardness and depth of cut. The responses were surface roughness and cutting force components in the hard turning. They used workpiece as AISI H11 steel with CBN tool. Mathematical models for all of the responses were developed using the response surface methodology (RSM). Results indicate that the cutting force components were influenced principally by the depth of cut and workpiece hardness; whereas, both feed rate and workpiece hardness have statistical significance on surface roughness.

D. I. Lalwani et al. [2] investigated the effect of cutting parameters on cutting forces and surface roughness in finish hard turning of MDN250 steel (equivalent to maraging steel) using coated ceramic tool. They plotted surface roughness counter for various cutting parameters combinations (viz. cutting speed, feed rate, and depth of cut). From that, they found that a good surface finish can be achieved for any level of cutting speed, when feed rate is low and depth of cut is high. Depth of cut and feed rate were the most significant factors influencing feed, cutting and thrust forces.

Dr. C. J. Rao et al. [3] conducted experiment with the help of Taguchi method (L27 design -3level and 3factor) while working with tool made up of ceramic and work material of AISI 1050 steel. The results indicated that it is feed rate has significant influence both on cutting force as well as surface roughness. Depth of cut has significant influence on cutting force. The interaction of feed and depth of cut was significant on cutting forces.

Gaurav Bartarya et al. [4] developed force prediction model during finish machining of EN31 steel (equivalent to AISI 52100 steel), which is having hardness of 60±2 HRC. They used hone edge uncoated CBN tool and analyzed the combination of machining parameter for better performance within a selected range of machining parameters. Depth of cut was found to be the most influencing parameter affecting the three cutting forces followed by feed.

Various researchers conducted experiments based on research methodologies such as Taguchi method, full factorial design of experiment, etc. They studied 3-4 process parameters, mainly cutting speed, feed, depth of cut, tool type and their levels were 3. They determined the effect of these parameters on surface roughness and cutting forces. In hard turning, magnitude of forces was more than in conventional turning. Researchers focused their work on surface roughness and cutting forces.

The main objective of this work is to establish and recommend a range for cutting parameters, viz., speed, feed and depth of cut for achieving specific goals such as lower cutting forces. The best combination of parameters will be found by experiments so that lower cutting forces were obtained. Based on the experimental results and subsequent analysis, recommendation will be made to the Mitsubishi materials, Pune.

3. RESPONSE SURFACE METHODOLOGY (RSM)

RSM is a group of statistical and mathematical techniques, which consists of fit of empirical models to the experimental data obtained in relation to experimental design.

General steps of RSM are-
1) Identifying input parameters and their levels for the responses under study through literature review.
2) Selection of experimental design (Central composite, Box- Behnken, etc.) and carry out the experiments accordingly.
3) Analysis of data through mathematical or statistical treatment and evaluation of model fitness.
4) Optimization of single or multiple response and displacement towards optimal region.

4. EXPERIMENTAL PROCEDURE

4.1 Workpiece material

Experiments are to be carried out on AISI D2 steel workpiece material with Mitsubishi CBN cutting tool on MTAB MAXTURN PLUS+ SIMENS (828D) CONTROL CNC Lathe. Application of AISI D2 steel includes high duty cutting tools (dies and punches), long run form rolls, and tube mill rolls, deep drawing tools for sheet and strip, thread rolling dies and pressing tools for ceramic industries. AISI D2 steel workpiece dimensions were 30 mm diameter and 90 mm length with 55(±2) HRC hardness.

Table 1: Chemical composition of AISI D2 steel

C	Mn	Si	Mo	Cr	V	Co
1.4-1.6	0.6	0.6	0.9	11-13	1.1	1

Table 2: Input parameters and their levels

Factor	Unit	Low level	High level
Cutting speed	m/min	30	130
Feed rate	mm/rev	0.1	0.5
Depth of cut	mm	0.2	1

4.2 Cutting tool and force measurement

Mitsubishi CBN tool (TNGA 160408G3 MB8025) was triangular in shape with 3 active corners. This tool is held in tool holder (WIDMAX ID OL MTJNR 2020 K16) and attached to Kistler dynamometer (Quartz 4-component dynamometer Type 9272) with lathe attachment. This dynamometer was attached to CNC lathe with special attachment plate. The dynamometer software (DynoWare Type 2825A) which is connected to dynamometer measures and record the data of all the three component of forces.

4.3 Experimental design

It consist of 20 runs (Full factorial design (2^3=8) + axial points (2*3=6) + central point (6)) as per central composite design of experiment.

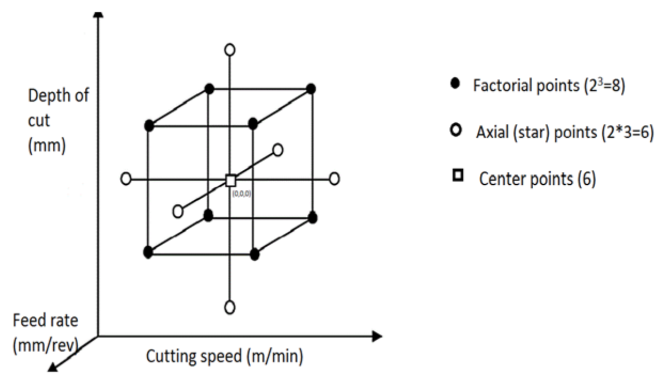

Fig. 1: Central composite design of experiment

It is noted that, from here, V: Cutting speed (m/min); F: Feed rate (mm/rev) and D: Depth of cut (mm).

Table 3: Experimental runs and measurement of responses

Sr. No.	V	F	D	FX (N)	FY (N)	FZ (N)
1	80	0.30	0.60	282.4	190.9	85.76
2	80	0.30	0.60	175.3	107.1	22.1
3	110	0.42	0.84	269.4	221.6	60.75
4	80	0.30	1.00	301.9	228.1	98.58
5	50	0.42	0.84	273.6	212.6	50.56
6	80	0.30	0.20	131.3	70.99	13.45
7	110	0.42	0.36	150.8	82.85	9.011
8	80	0.50	0.60	270.8	180.2	33.69
9	130	0.30	0.60	319.5	285.3	131.8
10	80	0.30	0.60	247.1	189	68.37
11	80	0.30	0.60	232.2	178.5	59.06

12	50	0.18	0.36	65.96	34.49	11.5
13	110	0.18	0.84	190.1	143.4	71.95
14	80	0.30	0.60	140.5	76.16	10.9
15	30	0.30	0.60	104.8	69.26	12.02
16	80	0.30	0.60	193.4	106.4	47.63
17	110	0.18	0.36	74.26	35.73	7.496
18	50	0.18	0.84	239.2	187.8	101.7
19	80	0.10	0.60	55.64	29.99	17.03
20	50	0.42	0.36	151.6	118.5	31.84

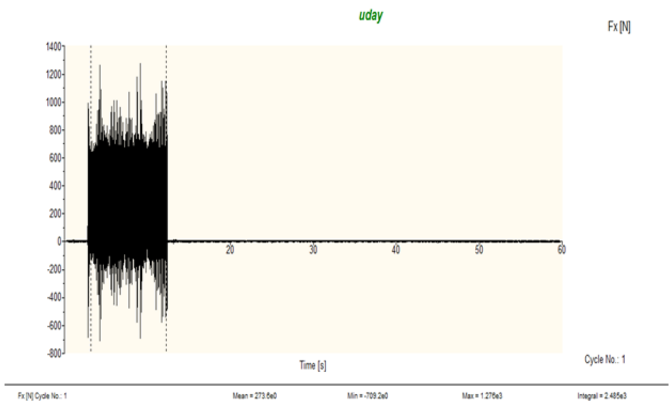

Fig. 2: Measurement of force F_X on Dynamometer software (DynoWare) for experiment no. 5

Fig. 2 shows DynoWare recording of data for post processing, where value of F_X is taken as 273.6 N. Similar data were obtained for all other values.

5. ANALYSIS OF F_X

Table 4: ANOVA table for F_X

Source	DF	Adj. SS	Adj. MS	F-value	p-value
Model	9	93401	10377.9	2.99	0.051
Linear	3	85886	28628.7	8.25	0.005
V	1	7279	7279	2.1	0.178
F	1	29780	29780	8.58	0.015
D	1	48827	48827	14.07	0.004
Square	3	6599	2199.7	0.63	0.61
V2	1	232	232	0.07	0.801
F2	1	6546	6546	1.89	0.2
D2	1	86	86	0.02	0.878
Interaction	3	916	305.4	0.09	0.965
V*F	1	160	160	0.05	0.834
V*D	1	462	462	0.13	0.723
F*D	1	294	294	0.08	0.777
Error	10	34697	3469.7		
Lack of fit	5	21296	4259.5	1.59	0.312
Pure error	5	13401	2680.2		
Total	19	128098			

Table 4 shows ANOVA for F_X. From that, it is observed that depth of cut and feed rate has p-value less than 0.05 (at 95% confidence level), which means that, they both has significant effect on F_X with contribution percentage of 38.12% and 23.12% respectively.

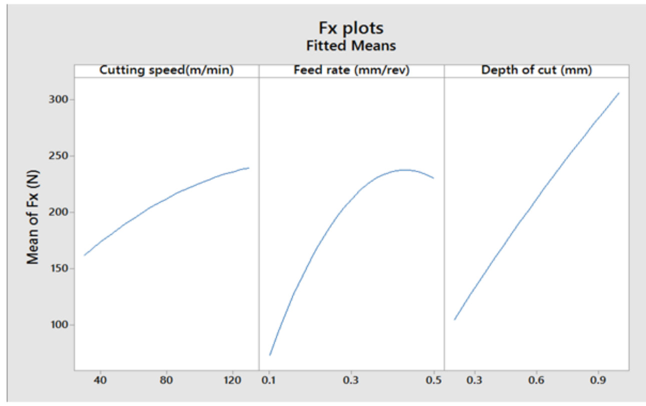

Fig. 3: Main effect for F_X

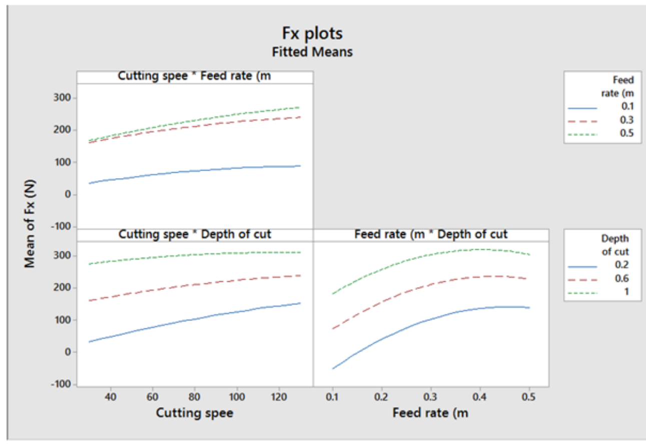

Fig. 4: Interaction plot for F_X

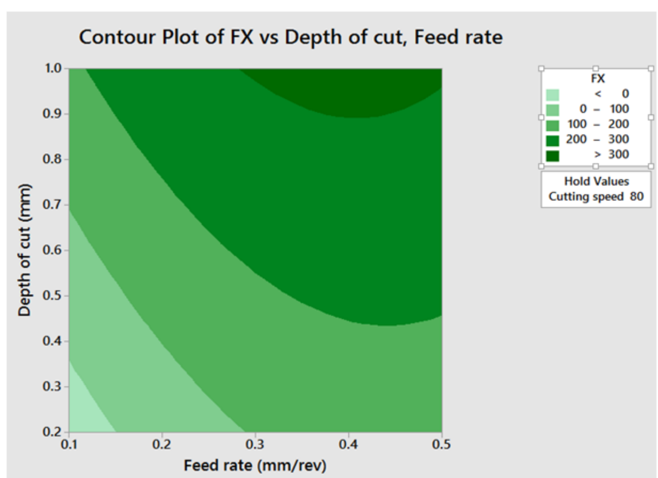

Fig. 5: Counter plot for F_X Vs. depth of cut and feed rate, when cutting speed is kept at 80 m/min

All the plots are obtained from MINITAB DOE software. The main effect plot for F_X (Fig. 2) shows that, F_X increases slightly with cutting speed, whereas it increases tremendously with depth of cut. For feed rate, F_X increases and then starts to decrease.

Interaction effect as shown in Fig. 3 and from ANOVA table for F_X shows that, (as lines are parallel) had no significant effect

Regression equation for F_X=-358 + [1.77*V] + [1324*F] + [453*D] - [0.0045*V^2] - [1547*F^2] - [43*D^2] + [1.27*V*F] - [1.07*V*D] - [214*F*D]

Counter plot for F_X (Fig. 4) shows that value of F_X is lower when both feed rate and depth of cut are lower. By fixing cutting force F_X value one can choose the region of operation and accordingly choose input variables from counter plot.

6. ANALYSIS OF F_Y

Table 5: ANOVA table for F_Y

Source	DF	Adj. SS	Adj. MS	F-value	p-value
Model	9	71336	7926.2	2.36	0.099
Linear	3	65735	21912	6.52	0.01
V	1	6309	6309	1.88	0.201
F	1	17349	17349	5.16	0.046
D	1	42078	42078	12.5	0.005
Square	3	5468	1823	0.54	0.664
V2	1	1340	1340	0.4	0.542
F2	1	3633	3633	1.08	0.323
D2	1	0	0	0	0.992
Interaction	3	133	44.4	0.01	0.998
V*F	1	34	34	0.01	0.922
V*D	1	0	0	0	0.995
F*D	1	99	99	0.03	0.867
Error	10	33611	3361		
Lack of fit	5	20861	4172	1.64	0.301
Pure error	5	12750	2550		
Total	19	104947			

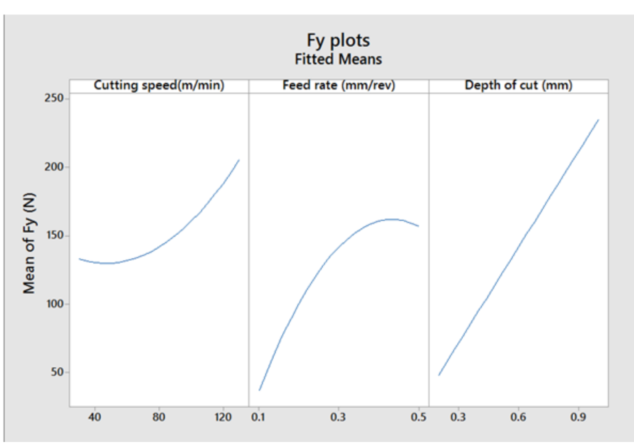

Fig. 6: Main effect plot for F_Y

ANOVA table for F_Y (Table 5), shows that, Depth of cut had the most significant effect on F_Y with contribution of 40.09%. Also, feed rate is also significant factor with contribution factor of 16.53%. Regression equation for F_Y (N) = -187 – [1.19*V] + [1001*F] + [276*D] + [0.0109*V^2] - [1123*F^2] – [3*D^2] + [0.58*V*F] - [0.02*V*D] - [124*F*D]

Main effect plot for F_Y (Fig. 6) depth of cut increases cutting forces sharply. As cutting speed increases, F_Y increases slightly.

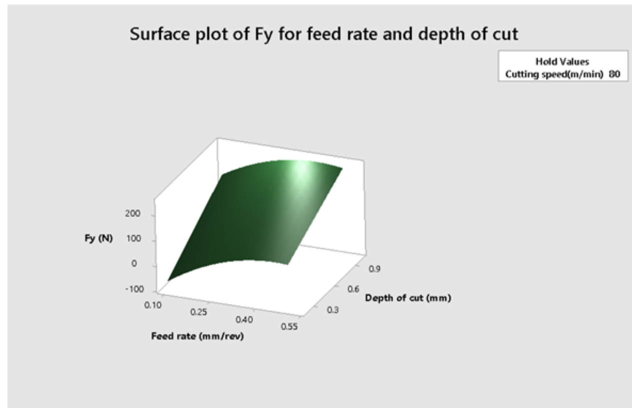

Fig. 7: Surface plot of F_Y for feed rate and depth of cut

Fig. 7 shows surface plot of F_Y for feed rate and depth of cut while cutting speed held constant at 80 m/min. From this surface plot, it is observed that F_Y is lower, when feed rate and depth of cut both are lower. With feed rate F_Y increases first and then decline at higher feed rate.

7. ANALYSIS OF F_Z

The depth of cut (contribution 38.78%) is the single most dominant factor for F_Z, which is observer from ANOVA table (table 5), as its p-value is less than 0.05 (95% confidence level).

Table 6: ANOVA table for F_Z

Source	DF	Adj. SS	Adj. MS	F-value	p-value
Model	9	14924.7	1658.3	1.55	0.251
Linear	3	11703.3	3901.09	3.65	0.052
V	1	1760.4	1760.37	1.65	0.228
F	1	11.4	11.38	0.01	0.92
D	1	9931.5	9931.51	9.29	0.012
Square	3	2273	757.65	0.71	0.568
V2	1	589.6	589.62	0.55	0.475
F2	1	1458.9	1458.92	1.36	0.27
D2	1	8.7	8.69	0.01	0.93
Interaction	3	948.4	316.15	0.3	0.828
V*F	1	55.7	55.73	0.05	0.824
V*D	1	6.6	6.61	0.01	0.939
F*D	1	886.1	886.1	0.83	0.384
Error	10	10688.3	1068.83		
Lack of fit	5	6683.5	1336.7	1.67	0.294
Pure error	5	4004.8	800.96		
Total	19	25613			

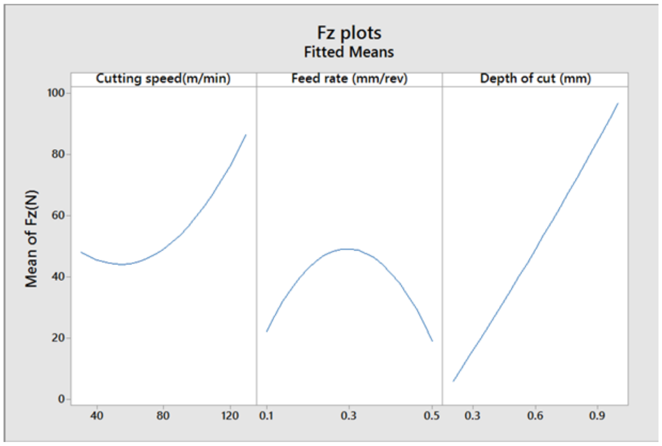

Fig. 8: Main effect plot for F_Z

Regression equation for F_Z (N) = - 103 – [1.08*V] + [583*F] + [198*D] + [0.00724* V^2] – [711* F^2] + [14* D^2] + [0.75*V*F] + [0.13*V*D] – [372*F*D]

Main effect plot for F_Z (Fig. 8) clearly indicates, with increase in depth of cut, cutting force component F_Z increases steeply. However, as feed rate increases, F_Z increase and then decrease forming a dome like figure.

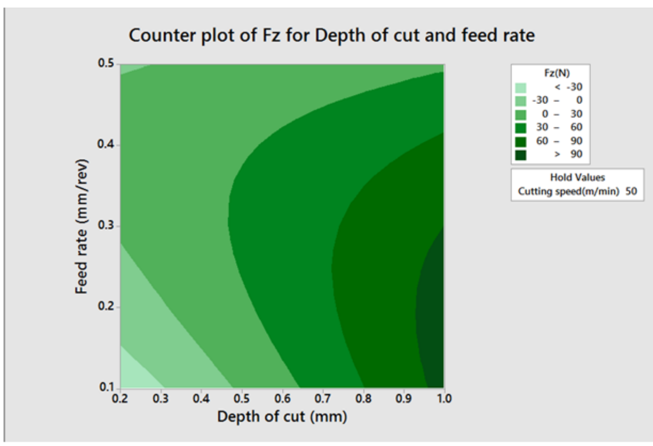

Fig. 9: Counter plot of F_Z for depth of cut and feed rate when cutting speed is kept constant at 50 m/min

The counter plot of F_Z (Fig. 9) indicates, for lower F_Z, both depth of cut and feed rate were held to be at lower values.

8. OPTIMIZATION OF FORCES

Using Minitab software, with response optimizer, all the three forces are optimized for target value of 0 N and composite desirability of 0.9501.

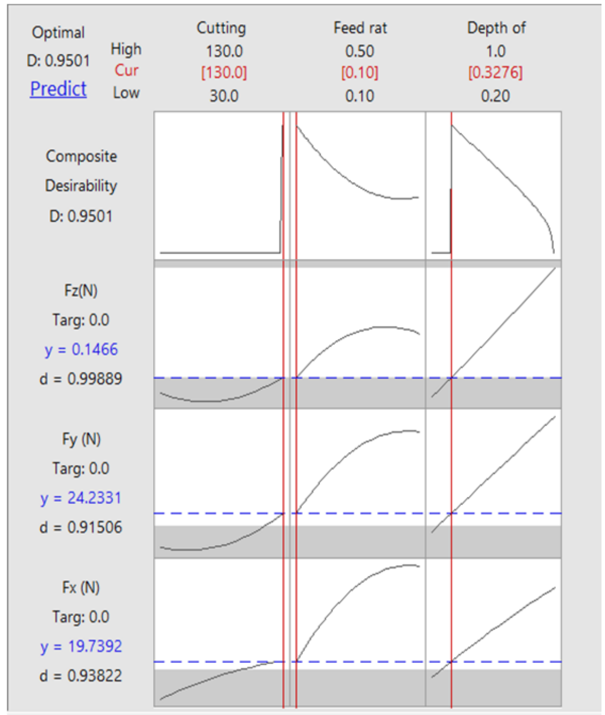

Fig. 10: Optimization plot for all the three force components

From the optimization plot (Fig. 10), it is clearly seen that, input parameters (within experimental range), are to be held as per the table 6.

Table 7: Optimized value of input parameter when overall composite desirability of 0.9501

Factor	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)
value	130	0.1	0.3276

9. CONCLUSION

- Cutting speed has no significant effect on any of the cutting force component.
- Square and 2- way interaction effect of each term were non-significant towards any of the forces.
- Depth of cut was the most significant factor with contribution of 38.12%, 40.09% and 38.78% towards F_X, F_Y and F_Z respectively.
- Feed rate had significant effect on F_X and F_Y with contribution of 23.25% and 16.53% respectively.
- For all the three force components, as depth of cut increases, cutting forces also increase sharply within experimental region.
- From counter plot and surface plot, one can select the output parameter and choose corresponding input parameter.

- Optimization of parameters were done with Minitab software for all three forces.

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