Effects of Cutting Parameters on Cutting Force, Surface Roughness and MRR in Hard Turning of AISI 4140 Alloy Steel

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Abstract – The goal of this research paper is to determine the effects of cutting parameters such as cutting speed, feed rate and depth of cut on the output responses such as cutting force, surface roughness and Material Removal Rate (MRR) in hard turning of AISI 4140 alloy steel. Taguchi method (L9 orthogonal array with 3 levels and 3 factors) was used for the experiments and analysis of variance (ANOVA) was performed to identify most significant factor. The results showed that the depth of cut (most significant factor) contributed 57.12%, feed rate (second most significant factor) contributed 41.47%, and cutting speed (least significant factor) contributed 0.09% for cutting force. The contribution of feed rate was 96.99%, whereas cutting speed and depth of cut contributed only 1.79% and 0.31%, respectively, for surface roughness. The contribution of depth of cut and feed rate was 38.51% and 53.32%, respectively, whereas the cutting speed contributed only 5.54% for material removal rate.

Keywords — ANOVA, Cutting Speed (VC), Feed Rate (f), Depth of Cut (d), Cutting Force (Fc), Surface Roughness (SR), MRR

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INTRODUCTION

Machining is the most important process to produce finished parts from work piece materials. The challenge of modern machining industries is mainly focused on the achievement of high quality, in terms of work piece dimensional accuracy, high surface finish, high production rate, less wear on the cutting tools, economy of machining in terms of cost saving and enhanced performance of the product with reduced environmental impact.

Surface roughness has received serious attention for many years. Surface roughness is the major indication of surface quality. Surface roughness of the material also depends on the tool geometry such as nose radius, rake angles, clearance angles and cutting condition such as cutting speed, feed rate and depth of cut.

The parameters such as surface roughness, cutting forces, material removal rate (MRR), power consumption, tool life, tool wear, cutting temperature decide the productivity, product quality and quality of machining. When compared to grinding process there is reduction in machining costs, increase in the flexibility and efficiency, part handling costs and finally decrease in the set-up times.

Turning in a lathe is to remove excess material from the work piece to produce a conical or a cylindrical surface. Machining of workpiece having hardness in the range of 45-70 HRc is considered under hard machining. Hard turning is the process machining in which the hardness value of the material is more than the 45HRc in order to obtain finished workpieces directly from hardened parts. Hard turning is best accomplished with cutting inserts made from CBN (Cubic Boron Nitride), cermet or ceramic. Alloy steel, bearing steels, hot and cold work tool steels, high speed steels, die steels, case hardened steels, etc., are the typical materials which are hard turned. Considerable research is being carried out in this area these days. A brief literature review of turning/hard turning is presented below.

Varaprasad. Bh et al. [1] studied the effects of cutting speed, feed rate and depth of cut on tool wear in the hard turning experimentally. AISI D3 steel was machined using Al2O3/TiC mixed ceramic tool with corner radius 0.8 mm. They develop a model and predicted tool flank wear of hard turned AISI D3 hardened steel using response surface methodology (RSM). To determine which parameter is more significant to responses and which is not, analysis of variance (ANOVA) was carried out on the experimental data. The combined effects of cutting speed, feed rate and depth of cut were investigated using contour plots and surface plots. Optimal cutting parameters cutting speed of 165 m/min, feed rate of 0.05 mm/rev and depth of cut of 0.3 mm to achieve a low tool wear of 0.148 mm. The significant parameter for tool flank wear is depth of cut. The feed rate and speed have very little influence on the total variation. The relationship between performance characteristics and cutting parameters is expressed by a multiple regression equation that can be used to estimate the expressed values of the performance level for any parameter levels. Dr. C. J. Rao et al. [2] reported the significance of influence of feed rate, depth of cut and cutting speed on surface roughness and cutting force while working with ceramic tool and work material of AISI 1050 steel. Experiments were conducted on CNC lathe with the help of Taguchi method (L27 design - 3 level and 3 factor). The experiments were conducted as per the design with randomization. ANOVA was carried out to study significant factors. The results indicated that it is the feed rate which has significant influence both on cutting force as well as surface roughness. Depth of cut has significant influence on cutting force, but no significant influence on surface roughness. The interaction of feed and depth of cut was significant on cutting forces whereas no interaction effect was significant for surface roughness. Hamdi Aouici et al. [3] studied the effects of cutting speed, feed rate, work piece hardness and depth of cut on surface roughness and cutting force components in the hard turning experimentally. AISI H11 steel was machined using CBN tool. Four-factor (cutting speed, feed rate, hardness and depth of cut) and three-level fractional experiment designs were conducted and statistical ANOVA were performed. Mathematical models for surface roughness and cutting force components were developed using the RSM. Results show that the cutting force components are influenced principally by the depth of cut and work piece hardness; on the other hand, both work piece hardness and feed rate have statistical significance on surface roughness. The cutting force and the feed force both are strongly influenced by the depth of cut, (56.77%) and (31.50%), respectively. On the opposite, the cutting speed has very little influence (0.14%). The best surface roughness was achieved at the lower feed rate and the highest cutting speed of the set experimental parameters. Hardeep Singh et al. [4] investigated the effect of cutting parameters like spindle speed, feed and depth of cut on surface finish and material removal rate on EN-8 using WIDIA Tool Bit CNMG120408. The results were optimized using Taguchi methodology. Results show that the feed rate, depth of cut and spindle speed approximate decreasing trend. The feed has the variable effect on surface roughness. It is interesting to note that spindle speed, feed rate and depth of cut for MRR have increasing trend. In the following section, experimental work is explained in detail.

EXPERIMENTAL WORK

A. *Workpiece Material and Cutting Tool*

AISI 4140 is the workpiece material used during experiment. Typical applications of AISI 4140 alloyed steel are shafts, gears, bolts, couplings, spindles, tool holders, sprockets, hydraulic machinery shafts etc.

The dimensions of workpiece are 30 mm diameter and 100 mm length. The chemical composition of workpiece, AISI 4140 alloyed steel, is represented in table I.

Table I Chemical composition of AISI 4140 alloy steel

Chemical composition of AISI 4140						
C	Si	Ma	P	S	Cr	Mo
0.38 / 0.43	0.2/ 0.35	0.75/ 1.0	≤0.035	≤0.040	0.8/ 1.1	0.15 / 0.2

B. *Hardening and Tempering*

- Cut the material into required dimensions (32mm diameter and 100mm length)
- Preheat the material at 450°Cfor 90 minutes
- Material is Heated at 850°C for 90 minute
- Oil quenching is done after heating for 30 minutes
- Tempering is done at 350°C for 2 hours

A pre-cut with a 2 mm depth of cut was performed on each work piece to get 30mm diameter and 100mm length. This was done in order to remove the rust layer or hardened top layer from the outside surface and to minimize any effect of in homogeneity on the experimental results. It is hardened to 55±2HRc.

C. *Cutting tool/insert*

TNGA 160408 S01020 L1-C TB 310 removable cutting tool insert was used during the experiment.

D. *Machine tool*

Experiments are performed at Government College of Engineering, Karad on a SIEMENS 828D controller, 2 axis CNC lathe, MAXTURN PLUS+.

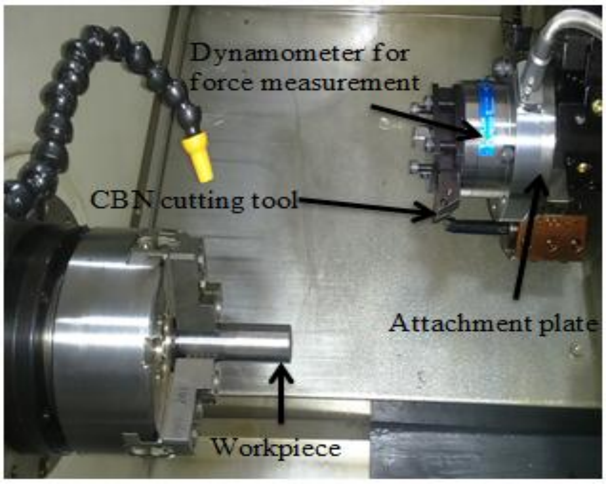

Fig 1 Experimental setup on CNC lathe

Table II Experimental set-up and condition

Machine tool	**2 Axis CNC lathe**
Workpiece	AISI 4140 alloy steel
Size	Φ100 mm × 30 mm
Cutting condition	With coolant
Tool holder	MTJNR 2020 K16
Surface roughness tester	SURFTEST (Mitutoyo Make)
Cutting force measuring instrument	Kistler dynamometer type 5070 (Swiss make)

Three cutting process parameters and three output responses are considered, which are listed in the following table III.

Table III Cutting process parameters and output responses

Cutting process parameters	**Output responses**
Cutting speed (m/min)	Cutting force (N)
Feed rate (mm/rev)	Surface roughness (μm)
Depth of cut (mm)	MRR (cc/min)

Following steps are performed to obtain ANOVA for different cutting process parameters-

A. DOE for pilot experimentation.

B. Deciding the levels for each cutting process parameter from pilot experimentation.

C. Design of experiment (Taguchi L9 OA) and perform the L9 OA.

D. Taguchi technique and ANOVA is done to find out the percentage contribution of each cutting process parameter.

A. DOE for pilot experimentation

It was decided to conduct the pilot study for hard turning operation. The conventional method of variation of one parameter at a time has been used to study the effect on cutting force, surface roughness and MRR with respect to important cutting process parameters. In first stage of experimentation it is observed that as the cutting speed increases MRR increases, and there is random increase and decrease in the value of surface roughness, hence to obtain lower cutting force, lower surface roughness and higher MRR it is desirable to keep cutting process parameters at suitable level and this is achieved by concept of normalization.

$$X_i^*(K) = \frac{Max\ X_i(K) - X_i(K)}{Max\ X_i(K) - Min\ X_i(K)} \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$X_i^*(K) = \frac{X_i(K) - Min\ X_i(K)}{Max\ X_i(K) - Min\ X_i(K)} \quad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Equation (1) is used for lower the better characteristics, i.e., for cutting force and surface roughness and equation (2) is used for higher the better characteristics, i.e., for MRR.

Pilot reading for each input cutting process parameters.

i) Cutting speed

Table IV Response table for cutting speed

f = 0.1 mm/rev, d = 0.3 mm			
Vc (m/min)	**Fc (N)**	**SR (μm)**	**MRR (cc/min)**
40	264	0.300	1.2
60	296	0.227	1.8
80	316	0.224	2.4
100	300	0.280	3.0
120	306	0.290	3.6
140	277	0.267	4.2
160	288	0.300	4.8
180	296	0.358	5.4
200	333	0.334	6.0

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Table V Normalized table for cutting speed

	Normalized values		
Vc (m/min)	Fc (N)	SR (μm)	MRR (cc/min)
40	1.000	0.433	0.000
60	0.539	0.977	0.125
80	0.246	1.000	0.250
100	0.477	0.582	0.375
120	0.393	0.507	0.500
140	0.809	0.679	0.625
160	0.650	0.432	0.750
180	0.534	0.000	0.875
200	0.000	0.179	1.000

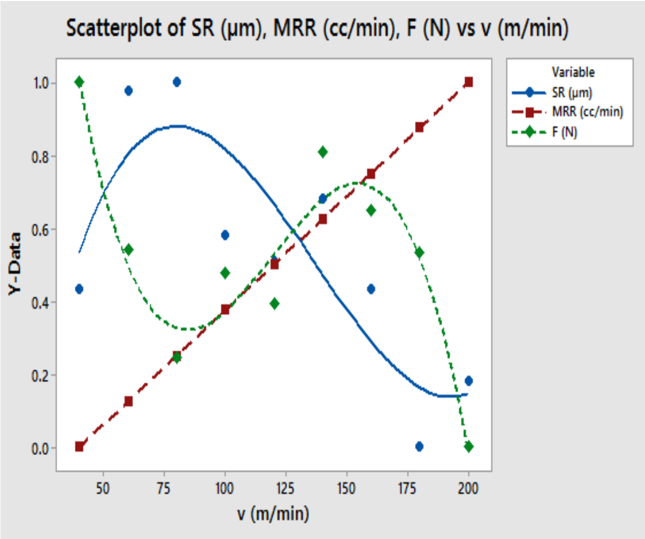

Fig 2 Normalized cutting force, surface roughness and MRR v/s cutting speed

ii) Depth of cut

Table VI Response table for depth of cut

f = 0.1 mm/rev, Vc = 100 m/min			
d (mm)	Fc (N)	SR (μm)	MRR (cc/min)
0.3	300	0.222	3.0
0.5	348	0.229	5.0
0.6	446	0.344	6.0
0.7	481	0.183	7.0
0.9	559	0.246	9.0
1.2	692	0.373	12.0

Table VII Normalized table for depth of cut

	Normalized values		
d (mm)	Fc (N)	SR (μm)	MRR (cc/min)
0.3	1.000	0.794	0.000
0.5	0.877	0.757	0.222
0.6	0.628	0.152	0.333
0.7	0.538	1.000	0.444
0.9	0.340	0.668	0.666
1.2	0.000	0.000	1.000

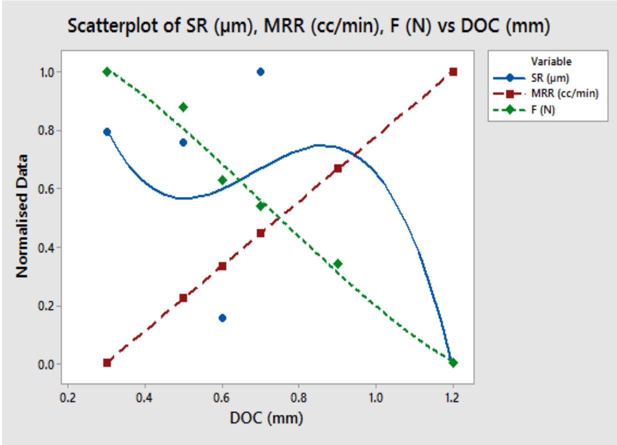

Fig 3 Normalized cutting force, surface roughness and MRR v/s depth of cut

iii) Feed rate

Table VIII Response table for feed rate

Vc = 100 m/min, d = 0.3 mm			
f (mm/rev)	Fc (N)	SR (μm)	MRR (cc/min)
0.05	199	0.177	1.5
0.08	244	0.225	2.4
0.11	263	0.285	3.3
0.14	288	0.297	4.2
0.17	348	0.406	5.1
0.20	338	0.582	6.0
0.23	337	1.076	6.9
0.26	414	1.214	7.8

Table IX Normalized table for feed rate

	Normalized values		
f (mm/rev)	Fc (N)	SR (μm)	MRR (cc/min)
0.05	1.000	1.000	0.000
0.08	0.790	0.953	0.142
0.11	0.702	0.895	0.285
0.14	0.584	0.884	0.428
0.17	0.307	0.779	0.571
0.20	0.355	0.609	0.714
0.23	0.357	0.130	0.857
0.26	0.000	0.000	1.000

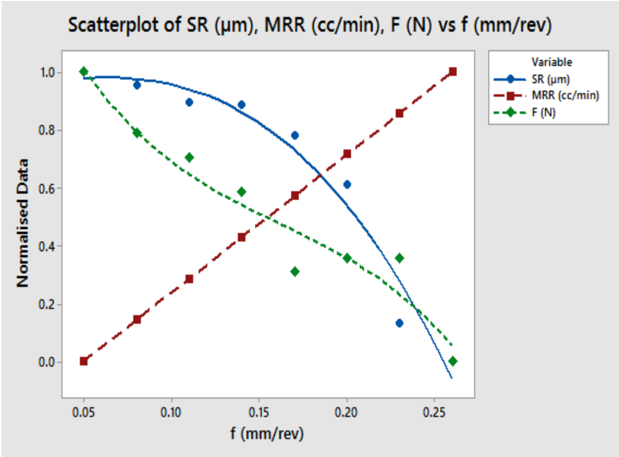

Fig 4 Normalized cutting force, surface roughness and MRR v/s feed rate

From above fig 2, fig 3 and fig 4, levels for cutting speed, feed rate and depth of cut are selected as shown in table 7. This level gives better results for cutting force, surface roughness and MRR.

B. *Selection of levels*

Table X shows that cutting process parameters level selection and their respective values for further experimentation.

Table X Cutting process parameters and their levels

Factors	Units	Level-1	Level-2	Level-3
Vc	m/min	120	140	160
d	mm	0.50	0.70	0.90
f	mm/rev	0.10	0.15	0.20

C. *Design of Experiment and perform the L9 OA*

Taguchi L-9 OA for 3 levels and three factors was used to perform further experiments.

Table XI Taguchi design L9 OA

Sr. No.	Vc (m/min)	d (mm)	f (mm/rev)
1	120	0.5	0.10
2	120	0.7	0.15
3	120	0.9	0.20
4	140	0.5	0.15
5	140	0.7	0.20
6	140	0.9	0.10
7	160	0.5	0.20
8	160	0.7	0.10
9	160	0.9	0.15

Table XII Experimental results L9 OA

Sr. No.	Fc (N)	MRR (cc/min)	SR (µm)
1	356	06.0	0.353
2	600	12.6	0.680
3	732	21.6	0.955
4	454	10.5	0.661
5	671	19.6	0.931
6	539	12.6	0.377
7	507	16.0	0.896
8	467	11.2	0.350
9	694	21.6	0.533

RESULTS AND DISCUSSION

Source	dof	Adj SS	Adj MS	F-Value	% cont.
Vc	2	0.00890	0.00445	1.96	1.79
D	2	0.00153	0.00077	0.34	0.31
f	2	0.48352	0.24176	106.49	96.99

Experiment was conducted to determine the effect of cutting speed, feed rate and depth of cut on the cutting force, surface roughness and MRR. Table XI and XII illustrate the experimental results of cutting force, surface roughness and MRR.

A. *Analysis of Variance (ANOVA)*

Analysis of variance (ANOVA) is used to determine the most significant factor affecting the performance measures.

Table XIII, XIV and XV show the results of ANOVA, for cutting force, surface roughness and MRR, respectively. The last columns of tables show the percentage contribution on the total variation indicating the degree of influence on the results.

Table XIII ANOVA result for cutting force

Source	dof	Adj SS	Adj MS	F-Value	% cont.
Vc	2	110	55.1	0.10	0.09
D	2	72075	36037.	62.99	57.12

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			4		
f	2	52838	26419.1	46.18	41.87
Error	2	1144	572.1		0.90
Total	8	126168			100.00

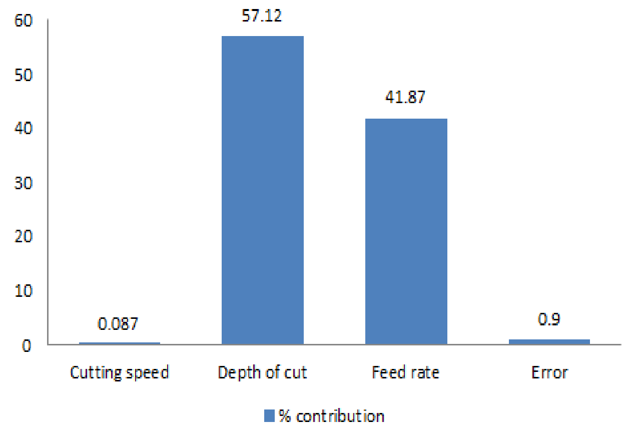

Fig 5 Percentage contribution of cutting process parameters for cutting force

In table XIII, the ANOVA results showed that the depth of cut (the most significant factor) contributed 57.12%, feed rate (the second most significant factor) contributed 41.47%, and cutting speed contributed the least, i.e., 0.09% for cutting force.

Table XIV ANOVA result for surface roughness

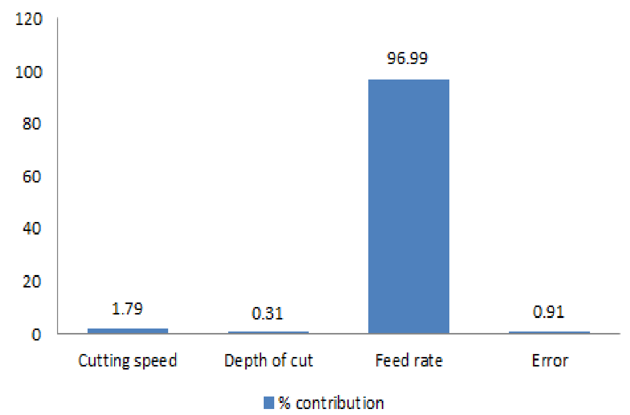

Fig 6 Percentage contribution of cutting process parameters for surface roughness

In table XIV, ANOVA results show that the contribution for feed rate is 96.99%, whereas cutting speed and depth of cut contributed only 1.79% and 0.31% for surface roughness.

Table XV ANOVA result for MRR

Source	dof	Adj SS	Adj MS	F-Value	% cont.
Vc	2	13.05	6.52	2.11	5.54
D	2	90.61	45.30	14.66	38.51
f	2	125.45	62.72	20.30	53.32
Error	2	6.18	3.09	-	2.63
Total	8	235.28	-	-	100.00

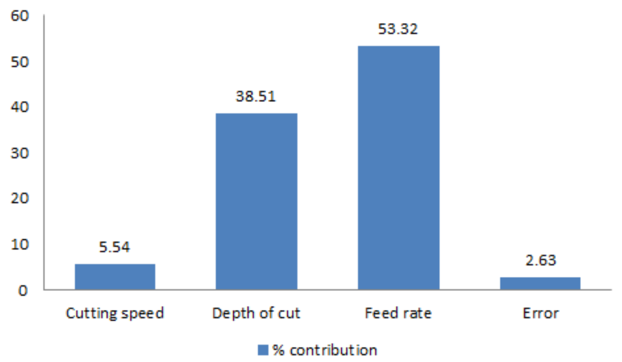

Fig 7 Percentage contribution of cutting process parameters for MRR

In table XV, the ANOVA results showed that the contribution for depth of cut and feed rate was 38.51% and 53.32%, whereas the cutting speed contributed only 5.54% for MRR.

B, *Main Effect Plot*

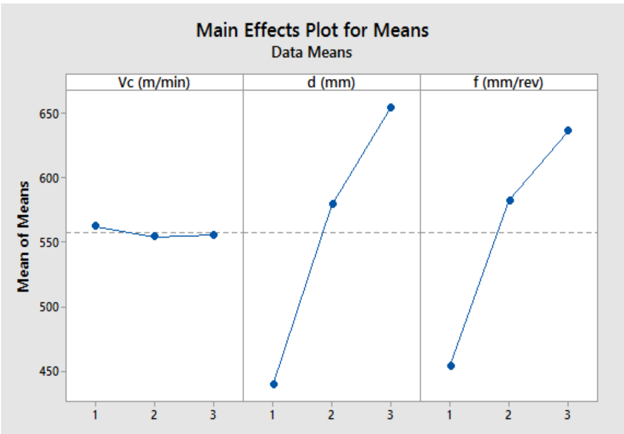

Fig 8 Main effect plot for cutting force

From above graphs it is seen that the depth of cut strongly changes cutting force. So it can be concluded that the depth of cut is more dominating factor in case of cutting force.

Table XVI Response table for means of cutting force

Level	Cutting speed (m/min)	Depth of cut (mm)	Feed rate (mm/rev)
1	562.7	439.0	454.0
2	554.7	579.3	582.7
3	556.0	655.0	636.7
Delta	8.0	216.0	182.7
Rank	3	1	2

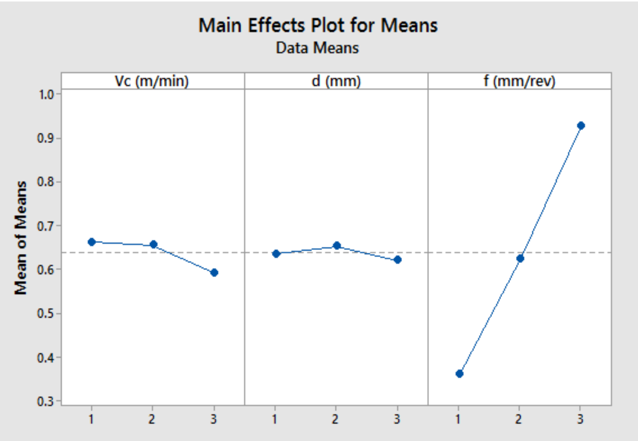

Fig 9 Main effect plot for surface roughness

From above graph it is clearly observed that the feed rate strongly changes surface roughness. So from above graph it can be concluded that the feed rate is more dominating factor.

Table XVII Response table for means of surface roughness

Level	Cutting speed (m/min)	Depth of cut (mm)	Feed rate (mm/rev)
1	0.6627	0.6367	0.3600
2	0.6563	0.6537	0.6247
3	0.5930	0.6217	0.9273
Delta	0.0697	0.0320	0.5673
Rank	2	3	1

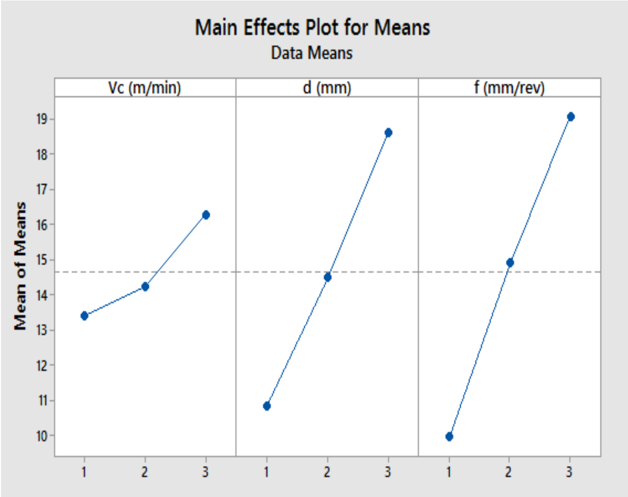

Fig 10 Main effect plot for MRR

From above graph it is seen that the feed rate strongly changes MRR. So from above graph it can be concluded that the feed rate is more dominating factor in case of MRR.

Table XVIII Response table for means of cutting force

Level	Cutting speed (m/min)	Depth of cut (mm)	Feed rate (mm/rev)
1	13.400	10.833	9.933
2	14.233	14.467	14.900
3	16.267	18.600	19.067
Delta	2.867	7.767	9.133
Rank	3	2	1

CONCLUSION

The objective of this research paper is to find out the most significant cutting process parameter in hard turning for cutting force, surface roughness and MRR.

The foremost conclusions which can be drawn are as follows:

1) The cutting force is strongly influenced by the depth of cut and feed rate, 57.12% and 41.47%, respectively. On the contrary, cutting speed has very little influence 0.087%.

2) The surface roughness is strongly influenced by the feed rate (96.99%), whereas cutting speed and depth of cut has insignificant influence, 1.79% and 0.31%, respectively.

3) MRR is strongly influenced by Feed rate and depth of cut, 53.32% and 38.51%,

respectively. On the contrary, cutting speed has very little influence 5.54%.

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