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Effect of Cutting Parameters on Surface Roughness and Cutting Force in Turning Mild Steel

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Abstract

The purpose of this paper is to study the effect of speed, feed and depth of cut on surface roughness (R_a) and cutting force (F_c) in turning mild steel using high speed steel cutting tool. Experiments were conducted on a precision centre lathe and the influence of cutting parameters was studied using analysis of variance (ANOVA)based on adjusted approach. Based on the main effects plots obtained through full factorial design, optimum level for surface roughness and cutting force were chosen from the three levels of cutting parameters considered. Linear regression equation of cutting force has revealed that feed, depth of cut, and the interaction of feed and depth of cut significantly influenced the variance. In case of surface roughness, the influencing factors were found to be feed and the interaction of speed and feed. As turning of mild steel using HSS is one among the major machining operations in manufacturing industry, the revelation made in this research would significantly contribute to the cutting parameters' optimization.

Keywords: Full factorial design, ANOVA, surface roughness, cutting force, interaction effect, adjusted approach.

Introduction

An area of research interest in turning is the analysis of cutting force, as minimum power consumption is a never ending endeavour. Among the Cutting force, Thrust force and Feed force the former prominently influences power consumption and the most common equation available for the estimation of Cutting force is given by (equation 1)[1]:

$$F_c = k_c \times DOC \times f \qquad (1)$$

Where, DOC = Depth of cut (mm), f = feed (mm/rev), k_c = Specific cutting energy coefficient (N/ mm^2)

According to equation 1, cutting force is influenced by the depth of cut, feed, and specific cutting energy coefficient. A lot of work is in progress to study this influence and construct the models for different tool and work force material so as to optimize the power consumption.

Another important parameter of research interest is Surface roughness of the work piece produced, as an optimum surface finish would influence performance of mechanical parts and cost of manufacture[2-7].

The surface finish of any given part is measured in terms of average heights and depths of peaks and valleys on the surface of the work piece[8]. But there are basically two streams of arguments on the influencing factors of surface roughness.

A popularly used model for estimating the surface roughness value is as follows (eqn. 2)[9-10].

$$R_a = f^2/8r \qquad (2)$$

Where, R_a = ideal arithmetic average (AA) surface roughness (µm), f = feed (mm/rev), r = cutter nose radius (mm).

The second stream of argument introduces speed also as an influencing factor of surface roughness and the governing equation is defined as (equation 3)[11].

$$R_a = C \times V \times f \qquad (3)$$

Where, V = speed (rpm), f = feed (mm/rev), C = Constant.

However, both the above two streams of arguments explain the surface roughness partially. Hence, there is always a need to go deeper into the investigation of influencing factors of surface roughness, particularly with respect to the interaction effects such as those between speed, feed, and depth of cut for different combinations of tool and work material.

Honet et al. reviewed contemporary work on heat generation and heat dissipation in high speed metal turning on coated materials and also briefly reviewed some temperature measurement techniques in metal cutting[12]. Considerable research effort has been made on the thermal problem in metal cutting, but the accuracy of the readings and the means by which the temperatures are measured are in question[13]. The unique tribological contact phenomenon, which occurs in metal cutting is highly localized and non-linear, and occurs at high temperatures, high pressures, and high strains. This has made it extremely difficult to predict in a precise manner or even assess the performance of various models developed for modelling the machining process. Even though thermal aspects are equally important, it is beyond the scope of this research.

Astakhov and Shvets studied force variations and their effects in metal-deforming technological processes[14]. They suggest that interaction of the energy waves propagating in the medium might affect the cutting force. They experimented and studied on the interaction between the deformation and the heat waves. The conclusions drawn from this paper reveals that the study of cutting force and the interaction between the deformation and heat waves can be very helpful in adopting the process which involves the least energy consumption.

The study on MDN250 steel using coated ceramic tool by Lalwani et al. also portrays the significance of accounting for surface roughness and cutting force[15]. MDN 250 steel finds its applications in Aerospace industry, Naval industry, etc., and hence, the results and the conclusions drawn here will prove to be helpful in the selection of optimum manufacturing conditions, thus contributing towards larger productivity[16,17].

Having realized the importance of the choice of most appropriate cutting conditions in metal cutting, this research primarily focuses on machining mild steel using HSS owing to its lower cost, ready availability, and a wide range of applications from automotives to domestic goods to constructional steel and many other machine elements such as keys, rings, fence posts etc. The influence of cutting parameters on cutting force and surface roughness can be studied effectively using Adjusted statistical approach[18-21].

Material and Methods

Machine: The experiment was carried out on the precision centre lathe (PSG A141) which enables high precision machining and production of jobs. The main spindle runs on high precision roller taper bearings and is made from hardened and precision drawn nickel chromium steel.

Technical Specifications are: centre height: 177.5mm, main motor power: 3hp, 30 longitudinal and transverse feeds.

The Tool: HSS tool with the alloying elements: manganese, chromium, tungsten, cobalt etc. has comparatively better resistance to heat and wear. Tool length of 75mm (approx.) was taken so as to minimize undesirable vibrations, which would influence cutting force and surface roughness. The lathe tool dynamometer was used for measuring cutting force and cutting process was continued until significant tool wear was observed[22-25]. The single point HSS tool specifications are as follows in figure - 2 and table - 1.

Table – 1
Tool Specification

Back Rake Angle	12º
Side Rake Angle	12º
End Relief	10º
End Cutting Edge Angle	30º
Side Cutting Edge Angle	15º
Nose Radius	0.8mm

Work piece: Work piece of standard dimensions was used for machining[26-28]: work piece diameter: 40mm, work piece length: 300mm (approx.).

Lathe Tool Dynamometer: The instrument used for the measurement of cutting force was IEICOS multi-component force indicator. It comprises of three independent digital display calibrated to display force directly using three component tool dynamometer. This instrument comprises independent DC excitation supply for feeding strain gauge bridges, signal processing systems to process and compute respective force values for direct independent display. Instrument operates on 230V, 50Hz AC mains. To record the force readings, IEICOS multi-component force indicator software was used. The data was obtained through a USB cable connected to the Dynamometer and stored on a computer.

Surface Roughness measurement: The instrument used to measure surface roughness was Surtronics 3+. For a probe movement of 4mm, surface roughness readings were recorded at three locations on the work piece and the average value was used for analysis.
Specifications of Surtronics 3+: gauge range: ±150um, probe movement (max): 25.4mm, traverse speed: 1mm/s.

Cutting Conditions and Experimental Procedure: Among the speed and feed rate combinations available on the Lathe, three levels of cutting parameters were selected[29]. It is given in table – 2.

Table-2
Factors and their Levels

Factor	Level 1	Level 2	Level 3
A: Speed (rpm)	228	360	450
B: Feed (mm/rev)	0.11	0.18	0.75
C: Depth of Cut (mm)	0.25	0.50	0.75

Full-Factorial design for three levels and three factors (3^k) yielded 27 experiments and two replicates were carried out. The standard order, run order, cutting parameters and responses are as shown in the Design of Experiments table[30,31]. It is given in table - 3.

Results and Discussion

Cutting Force Analysis: Cutting force increases almost linearly with the increase in depth of cut from 0.25mm to 0.75mm. Optimum conditions are achieved for a feed rate value of 0.18 mm/rev and a DOC value of 0.5mm. Figure-4, which is the main effects plot for cutting force indicates that cutting force is influenced significantly by depth of cut, feed rate, interaction effect of feed and depth of cut and interaction effect of speed, feed and depth of cut, whereas, speed has an insignificant influence on cutting force which is shown in table - 4. Further, the model adequately explains the total variance in cutting parameters and it is also reasonably a good fit (R^2 = 95.22%; R^2 adj. = 90.62%). It can also be noted through ANOVA that

Cutting force is not significantly influenced due to the interaction between speed and feed, however, there is an indication that at higher feed rate the influence may be significant[27]. Figure - 5 shows the interaction plot. Also, the table - 4 shows analysis of variance.

Figure-1
Experimental set-up

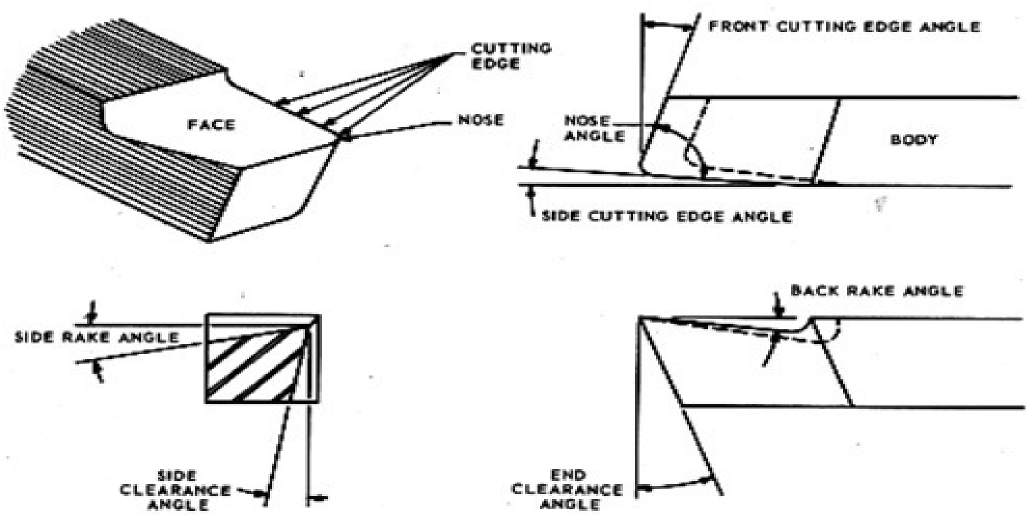

Figure-2
HSS tool nomenclature

Figure-3
IEICOS Multi-Component Force Indicator

Table-3
The DOE Table

Standard Order	Run Order	Speed (rpm): A	Feed (mm/rev): B	DOC (mm): C	Ra (µm)	Fc (kgf)	AB	BC	AC	ABC
39	1	360	0.11	0.75	5.95	21	39.6	0.0825	270	29.7
5	2	228	0.18	0.5	7.34	16	41.04	0.09	114	20.52
45	3	360	0.25	0.75	7.49	32	90	0.1875	270	67.5
26	4	450	0.25	0.5	8.73	26	112.5	0.125	225	56.25
36	5	228	0.25	0.75	6.75	25	57	0.1875	171	42.75
3	6	228	0.11	0.75	4.45	20	25.08	0.0825	171	18.81
19	7	450	0.11	0.25	5.61	5	49.5	0.0275	112.5	12.375
27	8	450	0.25	0.75	9.67	30	112.5	0.1875	337.5	84.375
53	9	450	0.25	0.5	8.2	23	112.5	0.125	225	56.25
52	10	450	0.25	0.25	8.53	22	112.5	0.0625	112.5	28.125
23	11	450	0.18	0.5	7.01	14	81	0.09	225	40.5
44	12	360	0.25	0.5	10.2	23	90	0.125	180	45
31	13	228	0.18	0.25	7.86	12	41.04	0.045	57	10.26
8	14	228	0.25	0.5	10	23	57	0.125	114	28.5
20	15	450	0.11	0.5	6.01	18	49.5	0.055	225	24.75
49	16	450	0.18	0.25	7.77	12	81	0.045	112.5	20.25
7	17	228	0.25	0.25	9.6	15	57	0.0625	57	14.25
38	18	360	0.11	0.5	5.66	16	39.6	0.055	180	19.8
47	19	450	0.11	0.5	8.66	18	49.5	0.055	225	24.75
14	20	360	0.18	0.5	6.32	13	64.8	0.09	180	32.4
22	21	450	0.18	0.25	6.91	12	81	0.045	112.5	20.25
2	s22	228	0.11	0.5	3.96	15	25.08	0.055	114	12.54
21	23	450	0.11	0.75	7.36	20	49.5	0.0825	337.5	37.125
41	24	360	0.18	0.5	8.53	14	64.8	0.09	180	32.4
33	25	228	0.18	0.75	8.35	22	41.04	0.135	171	30.78
16	26	360	0.25	0.25	10.6	19	90	0.0625	90	22.5
25	27	450	0.25	0.25	9.21	15	112.5	0.0625	112.5	28.125
12	28	360	0.11	0.75	7.93	21	39.6	0.0825	270	29.7
10	29	360	0.11	0.25	4.02	12	39.6	0.0275	90	9.9
42	30	360	0.18	0.75	8.06	24	64.8	0.135	270	48.6
40	31	360	0.18	0.25	5.25	12	64.8	0.045	90	16.2
54	32	450	0.25	0.75	11.07	26	112.5	0.1875	337.5	84.375
28	33	228	0.11	0.25	4.28	10	25.08	0.0275	57	6.27
6	34	228	0.18	0.75	6.53	23	41.04	0.135	171	30.78
9	35	228	0.25	0.75	8.93	25	57	0.1875	171	42.75
43	36	360	0.25	0.25	10.93	16	90	0.0625	90	22.5
32	37	228	0.18	0.5	8.9	19	41.04	0.09	114	20.52
30	38	228	0.11	0.75	4.92	25	25.08	0.0825	171	18.81
1	39	228	0.11	0.25	4.2	8	25.08	0.0275	57	6.27
13	40	360	0.18	0.25	7.6	12	64.8	0.045	90	16.2
48	41	450	0.11	0.75	7.86	20	49.5	0.0825	337.5	37.125
17	42	360	0.25	0.5	9.53	26	90	0.125	180	45
4	43	228	0.18	0.25	9.2	12	41.04	0.045	57	10.26
18	44	360	0.25	0.75	9.8	27	90	0.1875	270	67.5
51	45	450	0.18	0.75	6.93	17	81	0.135	337.5	60.75
15	46	360	0.18	0.75	9	26	64.8	0.135	270	48.6
34	47	228	0.25	0.25	9.61	16	57	0.0625	57	14.25
24	48	450	0.18	0.75	7.59	20	81	0.135	337.5	60.75
50	49	450	0.18	0.5	6.26	12	81	0.09	225	40.5
46	50	450	0.11	0.25	6.66	6	49.5	0.0275	112.5	12.375
37	51	360	0.11	0.25	6.73	14	39.6	0.0275	90	9.9
29	52	228	0.11	0.5	5.65	15	25.08	0.055	114	12.54
35	53	228	0.25	0.5	10.0	26	57	0.125	114	28.5
11	54	360	0.11	0.5	6.86	15	39.6	0.055	180	19.8

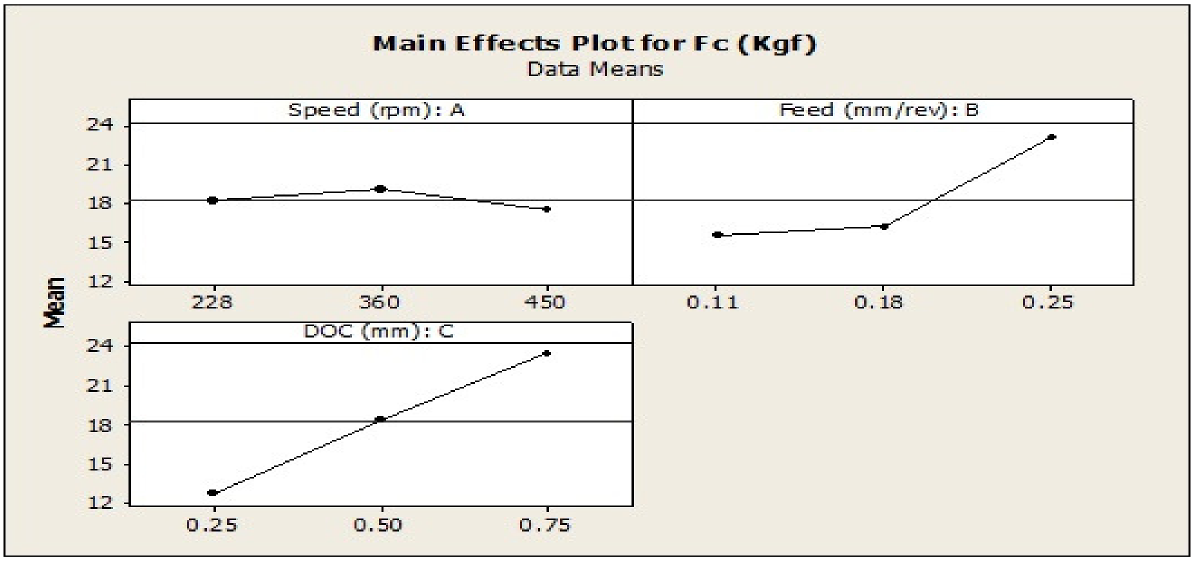

Figure-4
Main Effects Plot for Cutting Force F_c

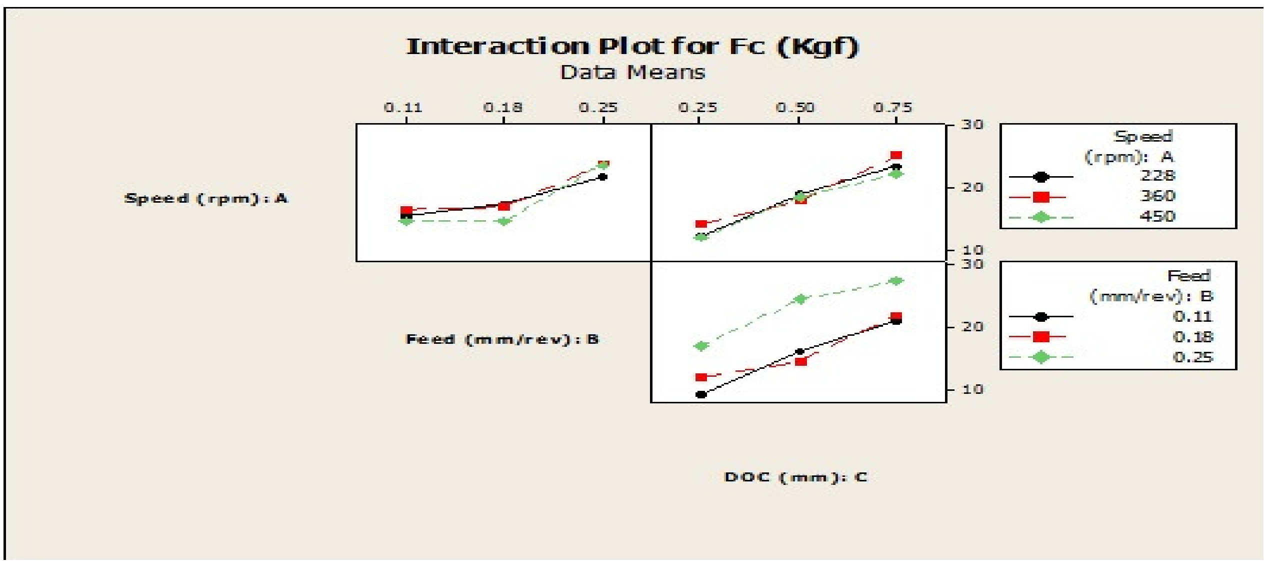

Figure-5
Interaction Plot for Cutting Force F_c

Table-4
ANOVA for cutting force

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Speed	2	20.481	20.481	10.241	2.91	0.072
Feed	2	625.815	625.815	312.907	88.93	0.000*
DOC	2	1046.370	1046.370	523.185	148.69	0.000*
Speed*Feed	4	36.407	36.407	9.102	2.59	0.059
Speed*DOC	4	28.519	28.519	7.130	2.03	0.119
Feed*DOC	4	50.519	50.519	12.630	3.59	0.018*
Speed*Feed*DOC	8	85.259	85.259	10.657	3.03	0.015*
Error	27	95.000	95.000	3.519	--	--
Total	53	1988.370	--	--	--	--
S = 1.87577 R^2 = 95.22% R^2(adj) = 90.62%						

*Significant influence ($\alpha = 0.05$).

Regression Analysis: The regression equation[13] is given in table - 5: F_c (kgf) = 0.6 - 0.0143*speed + 34.1*feed + 29.1*depth of cut + 0.092*speed - 25*feed*depth of cut - 0.0094*speed*depth of cut + 0.005*speed*feed*depth of cut.

Table-5
Regression Analysis

Predictor	Coef	SE Coef	T	P
Constant	0.57	13.92	0.04	0.967
Speed	-0.01430	0.03890	-0.37	0.715
Feed	34.12	73.70	0.46	0.646
DOC	29.08	25.77	1.13	0.265
Speed*Feed	0.0918	0.2060	0.45	0.658
Feed*DOC	-25.4	136.5	-0.19	0.853
Speed*DOC	-0.00935	0.07203	-0.13	0.897
Speed*Feed*DOC	0.0046	0.3814	0.01	0.990
S = 2.98097 R-Sq = 79.4% R-Sq(adj) = 76.3%				

Surface Roughness Analysis: The main effects plot indicates that surface roughness is significantly influenced by feed rate and the interaction between speed and feed, which are shown in figure - 6 and 7. Optimum condition for surface roughness is achieved at a feed rate value of 0.18 mm/rev for a speed of 360 rpm and depth of cut of 0.5mm.Further, the model satisfactorily explains the total variance in cutting parameters and it is also reasonably a good fit (R^2 = 84.25%; R^2 adj. = 69.09%). This is shown in table - 6.

Regression Analysis: The regression equation is given in table - 7: Ra (μm) = - 6.04 + 0.0187*speed + 85.4*feed + 7.42*depth of cut - 0.135*speed*feed - 69.9*feed*depth of cut - 0.0056*speed *depth of cut + 0.121*speed*feed*depth of cut.

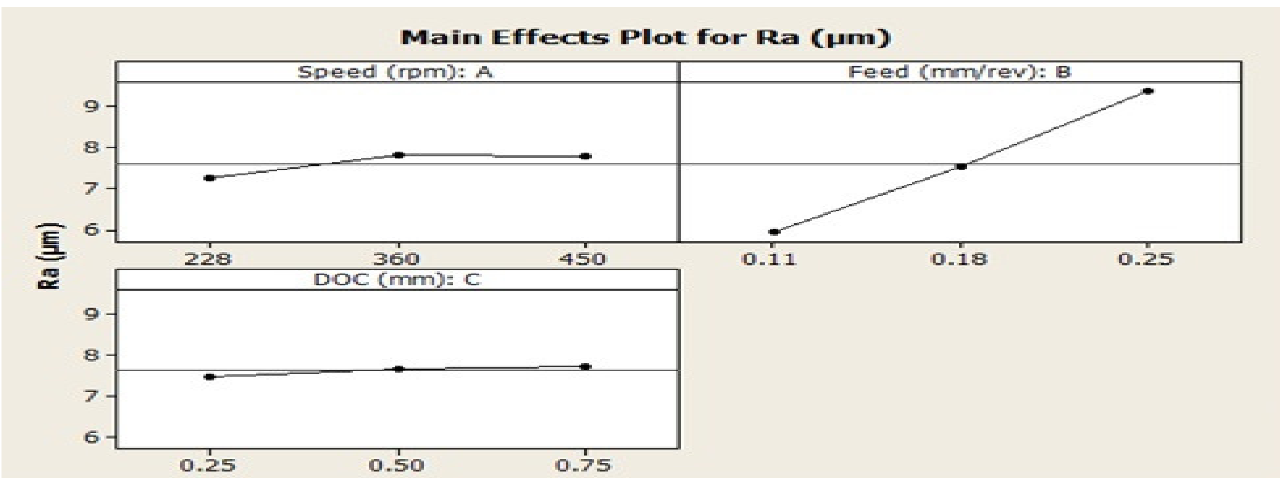

Figure-6
Main Effects Plot for Surface Roughness R_a

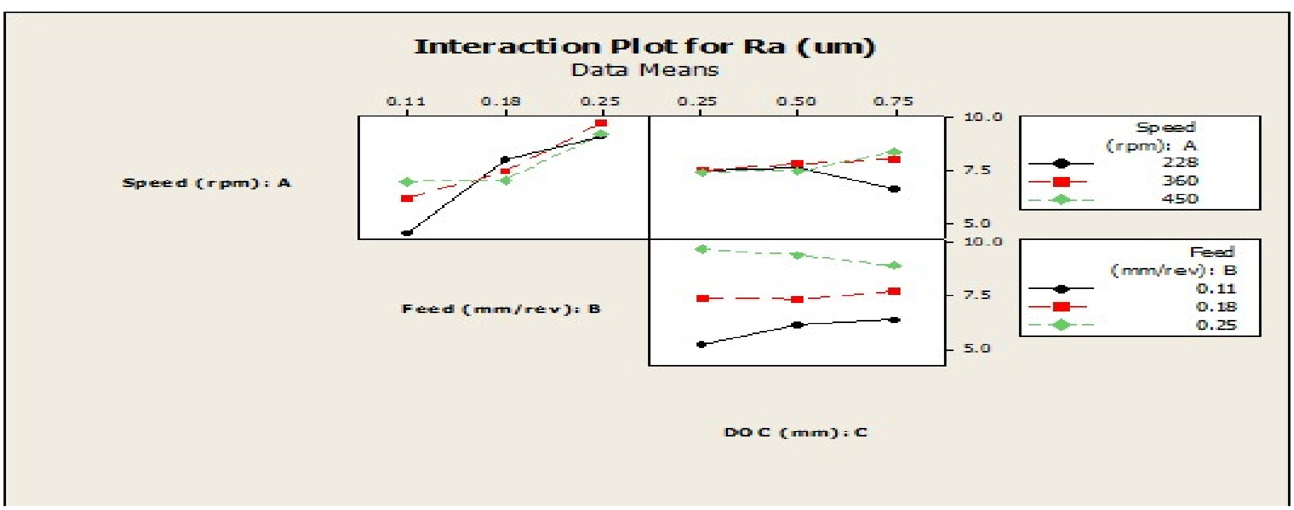

Figure-7
Interaction Plot for Surface Roughness R_a

Table-6
ANOVA for Surface Roughness

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Speed	2	3.497	3.497	1.748	1.63	0.215
Feed	2	107.302	107.302	53.651	49.88	0.000*
DOC	2	0.516	0.516	0.258	0.24	0.788
Speed*Feed	4	19.174	19.174	4.793	4.46	0.007*
Speed*DOC	4	7.230	7.230	1.808	1.68	0.184
Feed*DOC	4	6.274	6.274	1.568	1.46	0.242
Speed*Feed*DOC	8	11.368	11.368	1.421	1.32	0.275
Error	27	29.041	29.041	1.076	--	--
Total	53	184.401	--	--	--	--
S = 1.03711 R-Sq = 84.25% R-Sq(adj) = 69.09%						

*Significant influence ($\alpha = 0.05$).

Table-7
Regression Analysis

Predictor	Coef	SE Coef	T	P
Constant	-6.043	5.074	-1.19	0.240
Speed	0.01872	0.01418	1.32	0.193
Feed	85.38	26.87	3.18	0.003
DOC	7.424	9.395	0.79	0.433
Speed*Feed	-0.13516	0.07508	-1.80	0.078
Feed*DOC	-69.93	49.74	-1.41	0.166
Speed*DOC	-0.00561	0.02626	-0.21	0.832
Speed*Feed*DOC	0.1213	0.1390	0.87	0.387
S = 1.08666 R-Sq = 70.5% R-Sq(adj) = 66.1%				

Conclusion

The feed rate has significant influence on both the Cutting force and Surface roughness. Cutting Speed has no significant effect on the cutting force as well as the surface roughness of the chosen work piece. Depth of cut has a significant influence on cutting force, but an insignificant influence on surface roughness. In turning process optimization with respect to power consumption, the focus should be on choosing an appropriate combination of feed rate and depth of cut. Optimum surface roughness can be achieved by selecting relatively higher values of speed (>450 rpm), higher values of depth of cut (>0.75mm), and relatively lower values of feed rate (<0.11 mm/rev). In comparison to the sequential approach adopted in most of the contemporary research, this research has shown that adjusted approach can also be successfully used to fit a reasonably acceptable and generalized model provided, it is a mono-block design.

While the results declared through this experimental work may be generalized to a considerable extent while working on Mild Steel using HSS tool, the study is limited to the extreme range of values of the cutting parameters specified. Future research work may be directed towards applying Response Surface Methodology to further fine tune the optimization of cutting parameters, which was beyond the scope of this research, as it was mainly focussed towards the identification of most significantly influencing factors.

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