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Influence of cutting parameters on cutting force and surface finish in turning operation

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Abstract

This research reports the significance of influence of speed, feed and depth of cut on cutting force and surface roughness while working with tool made of ceramic with an Al_2O_3+TiC matrix (KY1615)and the work material of AISI 1050 steel (hardness of 484 HV). Experiments were conducted using Johnford TC35 Industrial type of CNC lathe. Taguchi method (L27 design with 3 levels and 3 factors) was used for the experiments. Analysis of variance with adjusted approach has been adopted. The results have indicated that it is feed rate which has significant influence both on cutting force as well as surface roughness. Depth of cut has a significant influence on cutting force, but has an insignificant influence on surface roughness. The interaction of feed and depth of cut and the interaction of all the three cutting parameters have significant influence on cutting force, whereas, none of the interaction effects are having significant influence on the surface roughness produced. If power consumption minimization is to be achieved for the best possible surface finish, the most recommended combination of feed rate and depth of cut is also determined.

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Keywords: Full Factorial design; ANOVA; Surface roughness; Cutting force; Interaction Effect; Adjusted approach.

1. Introduction

Turning operation using a single point cutting tool has been one of the oldest and popular methods of metal cutting. It has even replaced grinding in several applications with reduced lead time without affecting the surface quality ([1], [2], [3], [4] and [5]). In this connection, two important aspects which are widely studied in turning operations are cutting forces and surface roughness of the work-piece. Process parameter optimization is of great significance while looking into the process capability of any machining operation. Shaw [6] has emphasized the importance of studying cutting forces in turning operations as a number of factors are influenced by it, namely, surface accuracy, tool wear, tool breakage, cutting temperature, self-excited and forced vibrations, etc. A group of researchers including Ozel and Karpat [7] have found that cutting parameters (Feed rate, Cutting Speed, Depth of Cut, tool geometry and material properties of tool) directly influence the surface finish of machined components. However, among the cutting force, thrust force, and feed force, the former prominently influences power consumption and this work considers only cutting force as one of the endogenous factors.

Surface roughness is also a vital measure as it may influence frictional resistance, fatigue strength or creep life of machined components. As far as turned components are concerned, better surface finish (low surface roughness) is important as it can reduce or even completely eliminate the need of further machining. Many researchers have found that

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surface roughness has bearing on heat transmission, ability to hold lubricant, surface friction, wearing etc. Despite the fact that surface roughness plays a very important role in the utility and life of a machined component due to its dependence on several process parameters and numerous uncontrollable factors machining process has no complete control over surface finish obtained. So, the venture of controlling process parameters so as to produce best surface finish is an on-going process varying from various material to tool combinations and the machining conditions. The present work is aimed at studying the influence of the three major process parameters in a turning operation, namely, speed, feed and depth of cut on cutting force and surface roughness for a predefined combination of material and tool under the given set of machining conditions.

Cutting force is basically the product of specific cutting energy coefficient (N/mm^2), depth of cut (mm), and feed (mm/rev). Cutting force is generally resolved into three components, namely feed force (Fx), thrust force (Fy), and cutting force (Fz). The thrust force has been the focus of study in many studies, as it is the most important among the three which has major bearing on parameters of research interest. 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 [6]. But there are basically two streams of arguments on the influencing factors of surface roughness. The first defines surface roughness as the ratio of f^2 to 32r, where f is the feed (mm/rev) and r is cutter nose radius (mm) ([6], [8], and [9]). According to the second equation surface roughness is a function of speed (mm/min) and feed (mm/rev) [10]. As such both cutting force and surface roughness is not an easy parameter to quantify as it depends on several process parameters including speed, feed, and depth of cut for different combinations of tool and work material.

2. Literature review

Literature is very rich in terms of turning operation owing to its importance in metal cutting. The three important process parameters in this research are speed, feed and depth of cut. Surface roughness of a turned work-piece is dependent on these process parameters and also on tool geometry: nose radius, rake angle, side cutting edge angle and cutting edge. In addition, it also depends on the several other exogenous factors such as: work piece and tool material combination and their mechanical properties, quality and type of the machine tool used, auxiliary tooling, and lubricant used, and vibrations between the work piece, machine tool and cutting tool ([6], [11], [12], [13], [14], [15], [16] and [7]).

Lin et al. [17] adopted an abdicative network to construct a prediction model for surface roughness and cutting force. Feng and Wang [15] investigated the influence on surface roughness in finish turning operation by developing an empirical model through considering exogenous variables: work piece hardness (material), feed, cutting tool point angle, depth of cut, spindle speed, and cutting time. Suresh et al. [18] focused on machining mild steel by TiC-coated tungsten carbide (CNMG) cutting tools for developing a surface roughness prediction model by using Response Surface Methodology (RSM). Lee and Chen [19] have used ANN using sensing technique to monitor the effect of vibration produced by the motions of the cutting tool and work piece during the cutting process and developed an on-line surface recognition system. Kirby et al. [20] developed the prediction model for surface roughness in turning operation. Ozel and Karpat [7] worked on the prediction of surface roughness and tool flank wear by utilizing the neural network model in comparison with regression model. Kohli and Dixit [21] proposed a neural network based methodology with the acceleration of the radial vibration of the tool holder as feedback. Pal and Chakraborty [22] studied on development of a back propagation neural network model for prediction of surface roughness in turning operation and used mild steel work piece with HSS as the cutting tool for performing a large number of experiments. Sing and Lumar [23] studied on optimization of feed force through setting of optimal value of process parameters namely speed, feed and depth of cut in turning of EN24 steel with TiC coated tungsten carbide inserts. Ahmed [24] developed the methodology required for obtaining optimal process parameters for prediction of surface roughness in Al turning. Zhong et al. [25] predicted the surface roughness of turned surfaces using networks with seven inputs namely tool insert grade, work piece material, tool nose radius, rake angle, depth of cut, spindle speed, feed rate. Doniavi et al. [26] used RSM in order to develop empirical model for the prediction of surface roughness by deciding the optimum cutting condition in turning. Kassab and Khoshnaw [27] examined the correlation between surface roughness and cutting tool vibration for turning operation. Al-Ahmari [28] developed empirical models for tool life, surface roughness and cutting force for turning operation. Wang and Lan [29] used Orthogonal Array of Taguchi method coupled with grey relational analysis considering four parameters viz. speed, depth of cutting, feed rate, tool nose run off etc. for optimizing three responses: surface roughness, tool wear and material removal rate in precision turning on an ECOCA-3807 CNC Lathe. Sahoo et al. [30] studied for optimization of machining parameters combinations emphasizing on fractal characteristics of surface profile generated in CNC turning operation. Reddy et al. [31] adopted multiple regression model and ANN to deal with surface roughness prediction model for machining of aluminium alloys by CNC turning. Thamma [32] constructed the regression model to find out the optimal combination of process parameters in turning operation for Aluminium 6061 work piece. Fnides et al. [33] studied on machining of X38CrMoV5-1 steel treated at HRC by a mixed ceramic tool (insert CC650) to reveal the influence of cutting parameters: feed rate, cutting speed, depth of cut and flank wear on cutting forces as well as on surface roughness. Zawada-Tomkiewicz [34] used multi-parameter characterization of the surface in turning operation on an EN41Cr4 low chromium alloy steel, heat treated to the hardness of 58 HRC using polycrystalline cubic boron nitride tools. Davis [35] attempted optimization of surface roughness in dry as well as wet turning operation of EN24 and found that none of the factors (speed, feed and depth of cut) was found to be significant.

The above literature review clearly indicates that the study of feed, speed and depth of cut on cutting force and surface roughness has been very active since the past several decades, but there has been a continuous need to extend this study for the different combinations of tool and work material. The literature review also shows that there is no much of work undertaken with mixed ceramic tool and AISI 1050 steel work material combination, despite the fact that it is a widely used combination owing to its industrial applications.

Hence, the main objective of this research is to study the significance of influence of speed, feed and depth of cut on cutting force on the tool and surface finish of the work piece. In addition, the work also makes an attempt to optimize the cutting parameters for minimum energy consumption while turning the given material using the specified tool.

3. Research methodology

The research is basically a hypotheses testing research making use of design of experiments based on Taguchi method. Following hypotheses have been constituted for testing the main effect of the cutting parameters based on the literature review.

H_{1a}: Speed has significant influence on cutting force in turning operation.
H_{1o}: Speed has no significant influence on cutting force in turning operation.
H_{2a}: Speed has significant influence on surface roughness of the work-piece in turning operation.
H_{2o}: Speed has no significant influence on surface roughness of the work-piece in turning operation.
H_{3a}: Feed rate has significant influence on cutting force in turning operation.
H_{3o}: Feed rate has no significant influence on cutting force in turning operation.
H_{4a}: Feed rate has significant influence on surface roughness of the work-piece in turning operation.
H_{4o}: Feed rate has no significant influence on surface roughness of the work-piece in turning operation.
H_{5a}: Depth of cut has significant influence on cutting force in turning operation.
H_{5o}: Depth of cut has no significant influence on cutting force in turning operation.
H_{6a}: Depth of cut has significant influence on surface roughness of the work-piece in turning operation.
H_{6o}: Depth of cut has no significant influence on surface roughness of the work-piece in turning operation.

3.1. Machine and the materials

The turning operation was conducted using Johnford TC35 Industrial type of CNC lathe machine with a range of spindle speed from 50 rpm to 3500 rpm, and a 10 KW motor drive. The cutting tool was a mixed ceramic with an Al_2O_3+TiC matrix, which is designated by KY1615. The insert type was TNGA 160408-KY1615 and TNGA 160408-KY4400. The material used was a hardened AISI 1050 steel (hardness of 484 HV). These bars (40 mm in diameter and 300 mm in length) were machined under dry condition. The work material bars were trued, centred and cleaned by removing a 1 mm depth of cut from the outside surface, prior to the actual machining tests.

3.2. Cutting force measurement

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.

3.3. 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

3.4. Cutting conditions and experimental procedure

Among the speed, feed rate, and depth of cut combinations available on the Lathe, three levels of cutting parameters were selected based on similar earlier studies (Table – 1).

Table - 1: Factors and their Levels

Factor	**Level 1**	**Level 2**	**Level 3**
A: Speed (m/min)	50	75	95
B: Feed (mm/rev)	0.05	0.10	0.15
C: Depth of Cut (mm)	0.25	0.50	0.75

Taguchi design L-27 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 in the design of experiments are given table - 2.

Table 2: Design matrix with responses (cutting force and surface roughness)

Standard Order	Run Order	Speed (m/min) A	Feed (mm/rev) B	DOC (mm) C	Ra (μm)	Fy (kgf)	AB	BC	AC	ABC
39	1	75	0.05	0.75	5.95	23.00	39.60	0.08	270.00	29.70
5	2	50	0.10	0.50	7.34	17.00	41.04	0.09	114.00	20.52
45	3	75	0.15	0.75	7.49	33.00	90.00	0.19	270.00	67.50
26	4	95	0.15	0.50	8.73	27.00	112.50	0.13	225.00	56.25
36	5	50	0.15	0.75	6.75	25.00	57.00	0.19	171.00	42.75
3	6	50	0.05	0.75	4.45	20.00	25.08	0.08	171.00	18.81
19	7	95	0.05	0.25	5.61	15.00	49.50	0.03	112.50	12.38
27	8	95	0.15	0.75	9.67	30.00	112.50	0.19	337.50	84.38
53	9	95	0.15	0.50	8.20	23.00	112.50	0.13	225.00	56.25
52	10	95	0.15	0.25	8.53	22.00	112.50	0.06	112.50	28.13
23	11	95	0.10	0.50	7.01	14.00	81.00	0.09	225.00	40.50
44	12	75	0.15	0.50	10.20	23.00	90.00	0.13	180.00	45.00
31	13	50	0.10	0.25	7.86	12.00	41.04	0.05	57.00	10.26
8	14	50	0.15	0.50	10.00	23.00	57.00	0.13	114.00	28.50
20	15	95	0.05	0.50	6.01	18.00	49.50	0.06	225.00	24.75
49	16	95	0.10	0.25	7.77	12.00	81.00	0.05	112.50	20.25
7	17	50	0.15	0.25	9.60	15.00	57.00	0.06	57.00	14.25
38	18	75	0.05	0.50	5.66	16.00	39.60	0.06	180.00	19.80
47	19	95	0.05	0.50	8.66	18.00	49.50	0.06	225.00	24.75
14	20	75	0.10	0.50	6.32	13.00	64.80	0.09	180.00	32.40
22	21	95	0.10	0.25	6.91	12.00	81.00	0.05	112.50	20.25
2	22	50	0.05	0.50	3.96	15.00	25.08	0.06	114.00	12.54
21	23	95	0.05	0.75	7.36	20.00	49.50	0.08	337.50	37.13
41	24	75	0.10	0.50	8.53	14.00	64.80	0.09	180.00	32.40
33	25	50	0.10	0.75	8.35	22.00	41.04	0.14	171.00	30.78
16	26	75	0.15	0.25	10.60	19.00	90.00	0.06	90.00	22.50
25	27	95	0.15	0.25	9.21	15.00	112.50	0.06	112.50	28.13
12	28	75	0.05	0.75	7.93	21.00	39.60	0.08	270.00	29.70

10	29	75	0.05	0.25	4.02	12.00	39.60	0.03	90.00	9.90
42	30	75	0.10	0.75	8.06	24.00	64.80	0.14	270.00	48.60
40	31	75	0.10	0.25	5.25	12.00	64.80	0.05	90.00	16.20
54	32	95	0.15	0.75	11.07	26.00	112.50	0.19	337.50	84.38
28	33	50	0.05	0.25	4.28	10.00	25.08	0.03	57.00	6.27
6	34	50	0.10	0.75	6.53	23.00	41.04	0.14	171.00	30.78
9	35	50	0.15	0.75	8.93	25.00	57.00	0.19	171.00	42.75
43	36	75	0.15	0.25	10.93	16.00	90.00	0.06	90.00	22.50
32	37	50	0.10	0.50	8.90	19.00	41.04	0.09	114.00	20.52
30	38	50	0.05	0.75	4.92	25.00	25.08	0.08	171.00	18.81
1	39	50	0.05	0.25	4.20	8.00	25.08	0.03	57.00	6.27
13	40	75	0.10	0.25	7.60	12.00	64.80	0.05	90.00	16.20
48	41	95	0.05	0.75	7.86	20.00	49.50	0.08	337.50	37.13
17	42	75	0.15	0.50	9.53	26.00	90.00	0.13	180.00	45.00
4	43	50	0.10	0.25	9.20	12.00	41.04	0.05	57.00	10.26
18	44	75	0.15	0.75	9.80	27.00	90.00	0.19	270.00	67.50
51	45	95	0.10	0.75	6.93	17.00	81.00	0.14	337.50	60.75
15	46	75	0.10	0.75	9.00	26.00	64.80	0.14	270.00	48.60
34	47	50	0.15	0.25	9.61	16.00	57.00	0.06	57.00	14.25
24	48	95	0.10	0.75	7.59	20.00	81.00	0.14	337.50	60.75
50	49	95	0.10	0.50	6.26	12.00	81.00	0.09	225.00	40.50
46	50	95	0.05	0.25	6.66	6.00	49.50	0.03	112.50	12.38
37	51	75	0.05	0.25	6.73	14.00	39.60	0.03	90.00	9.90
29	52	50	0.05	0.50	5.65	15.00	25.08	0.06	114.00	12.54
35	53	50	0.15	0.50	10.01	26.00	57.00	0.13	114.00	28.50
11	54	75	0.05	0.50	6.86	15.00	39.60	0.06	180.00	19.80

4. Result analysis

4.1.Cutting force analysis

The analysis of variance (ANOVA) results very clearly support the hypotheses H_3 & H_5, indicating that both feed and depth of cut have significant influence on cutting force (table 3). This is in agreement with earlier research undertaken by a group

Table - 3: ANOVA of Cutting Force.

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**Hypothesis**
Speed	2	20.48	20.28	10.24	2.91	0.072	--
Feed	2	625.82	625.82	312.91	88.93	0.000*	Supported
DOC	2	1046.37	1046.37	523.19	148.69	0.000*	Supported
Speed*Feed	4	36.41	36.41	9.10	2.59	0.059	--
Speed*DOC	4	28.52	28.52	7.13	2.03	0.119	--
Feed*DOC	4	50.52	50.52	12.63	3.59	0.018*	Supported
Speed*Feed*DOC	8	85.26	85.26	10.65	3.01	0.015*	Supported
Error	27	95.00	95.00	3.52	--	--	
Total	53	1988.37	--	--	--	--	
S = 1.88 R-Sq = 95.22% R-Sq(adj) = 90.62%							

*Significant influence ($\alpha = 0.05$)

of researchers which was undertaken with different tool and material combination ([5], [36]). This can be seen in the main effect plot of cutting force (figure 1). Further, it can be observed that the interaction effect of feed rate & depth of cut and the interaction of all the three cutting parameters have significant influence on cutting force (table 3; figure 2). The R-square and adjusted R-square values above 90%, indicates that the model fit is on the higher side of the acceptable limit (figure 3). The regression coefficients of cutting force are given in table 4. The regression equation for cutting force is as follows. However, it can be observed that in the regression equation, it is only the depth of cut which has significant influence. Again, the R-square and R-square adjusted are both above 75%, and hence, the model is moderately a good fit. The regression equation is as follows.

F_y (kgf) = 4.35 - 0.107 *speed + 29.8 *feed + 25.8 *depth of cut + 0.129 *speed - 9.1 *feed*depth of cut –
- 0.043*speed*feed*depth of cut+/- €

Where, € = regression error

Table - 4: Regression Analysis Cutting Force.

Predictor	**Coef**	**SE Coef**	**T**	**P**
Constant	4.35	5.12	0.85	0.40
Speed	-0.11	0.07	-1.51	0.14
Feed	29.81	52.66	0.57	0.57
DOC	25.84	6.5	4.00	0.000
Speed*Feed	0.13	0.09	1.36	0.18
Feed*DOC	-9.06	52.08	-0.17	0.86
Speed*Feed*DOC	-0.04	0.11	-0.38	0.71
S = 2.93	**R-Sq = 79.7%**	**R-Sq(adj) = 77.1%**		

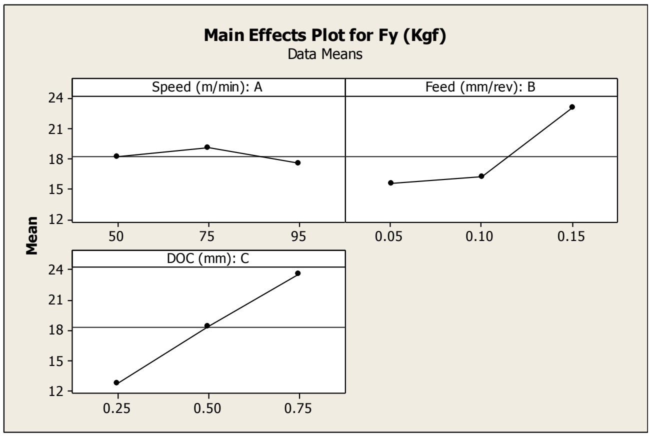

Figure - 1: Main Effects Plot for Cutting Force F_y.

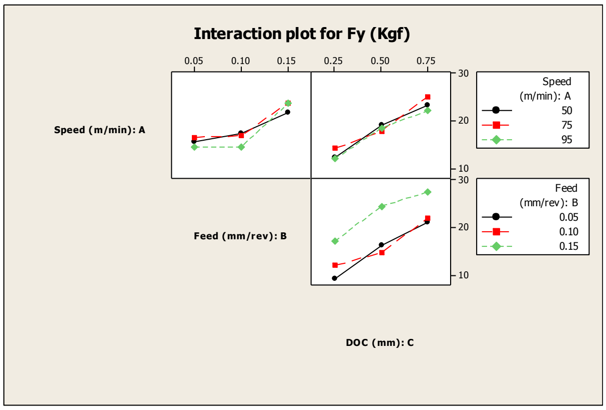

Figure - 2: Interaction Plot for Cutting Force F_c

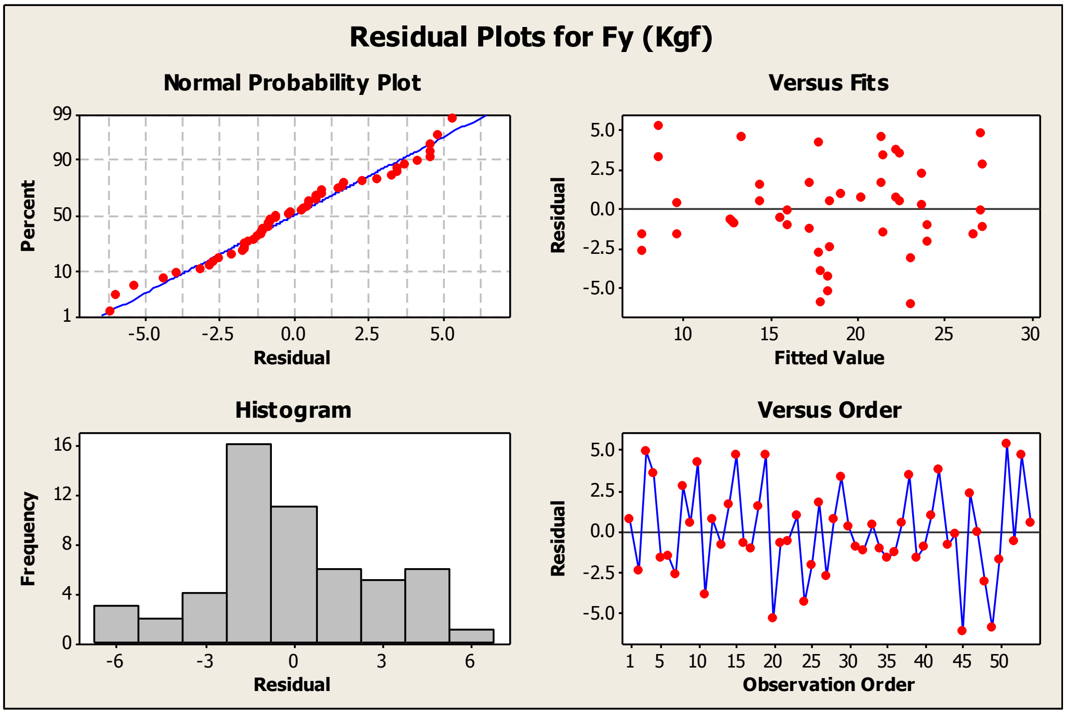

Figure - 3: Residual Plot for Cutting force F_y (kgf.)

The power consumption minimization was also one of the objectives of this research. So, having observed through the analysis of variance that feed rate and depth of cut have significant influence on the cutting force which in turn has bearing on the power consumption, the contour plot was developed. It can be observed that for power consumption minimization, the focus should be on choosing an appropriate combination of feed rate (< 0.06 mm/rev) and depth of cut (<0.15 mm) (figure 4).

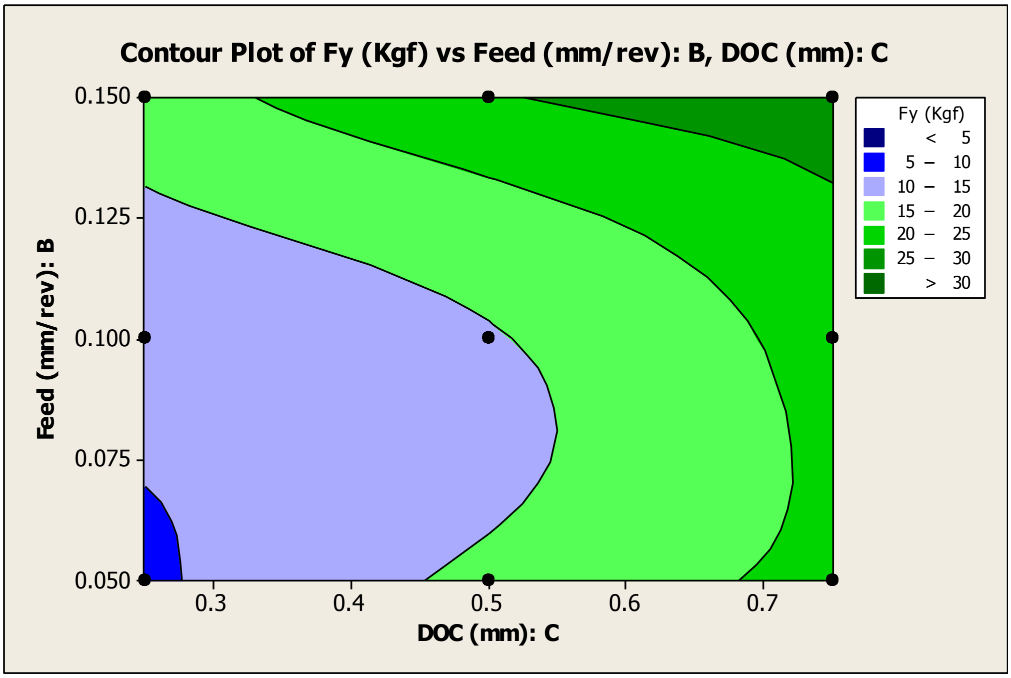

Figure - 4: Contour Plot for Cutting force F_y (kgf).

4.2. Surface roughness analysis

The surface roughness analysis of variance (Table 5; figure 5) indicates that the hypothesis H_4 stands supported which claims that feed rate has significant influence on surface roughness. Further, among the interaction effects, interaction between speed and feed has significant influence on surface finish (figure 6). R-square of 84.25% indicates a good model fit, but R-square adjusted of 60.09% is slightly on the lower side of goodness of fit, but in the acceptable limit (figure 7).

Table - 5: ANOVA for Surface Roughness

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**Hypothesis**
Speed	2	3.50	3.50	1.75	1.63	0.215	--
Feed	2	107.30	107.30	53.65	49.88	0.000*	Supported
DOC	2	0.52	0.52	0.26	0.24	0.79	--
Speed*Feed	4	19.17	19.17	4.79	4.46	0.01*	Supported
Speed*DOC	4	7.23	7.23	1.81	1.68	0.18	--
Feed*DOC	4	6.27	6.27	1.57	1.46	0.24	--
Speed*Feed*DOC	8	11.37	11.37	1.42	1.32	0.28	--
Error	27	29.04	29.04	1.08	--	--	
Total	53	184.40	--	--	--	--	
S = 1.037 R-Sq = 84.25% R-Sq(adj) = 69.09%							

*Significant influence (α = 0.05).

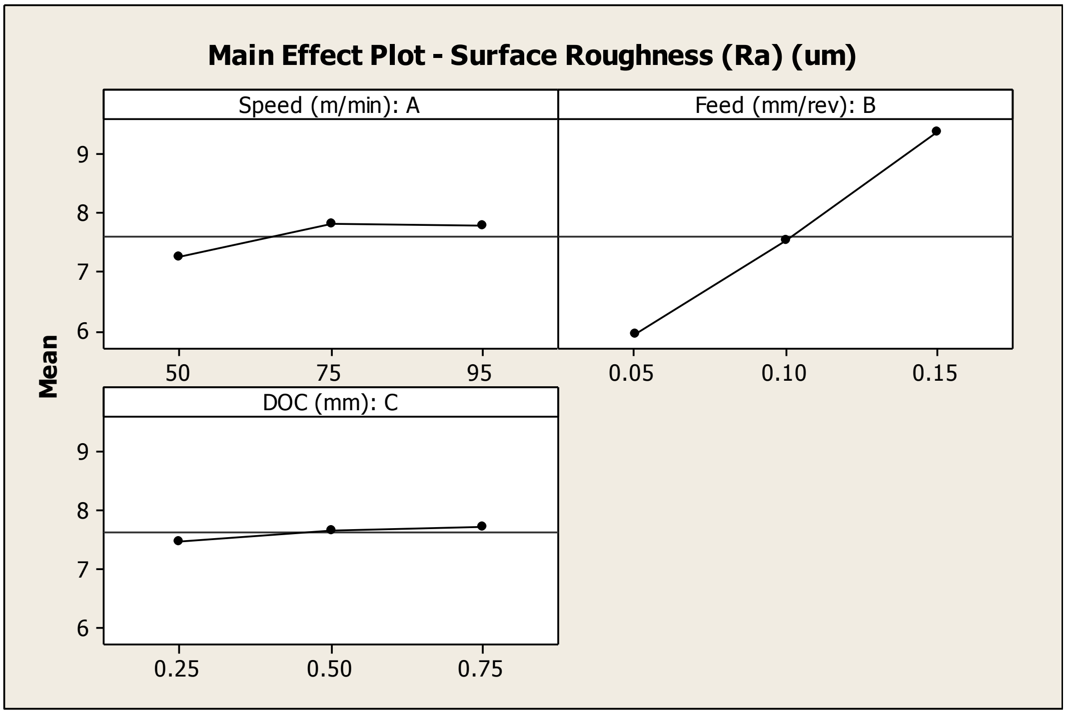

Figure - 5: Main Effects Plot for Surface Roughness R_a (μm)

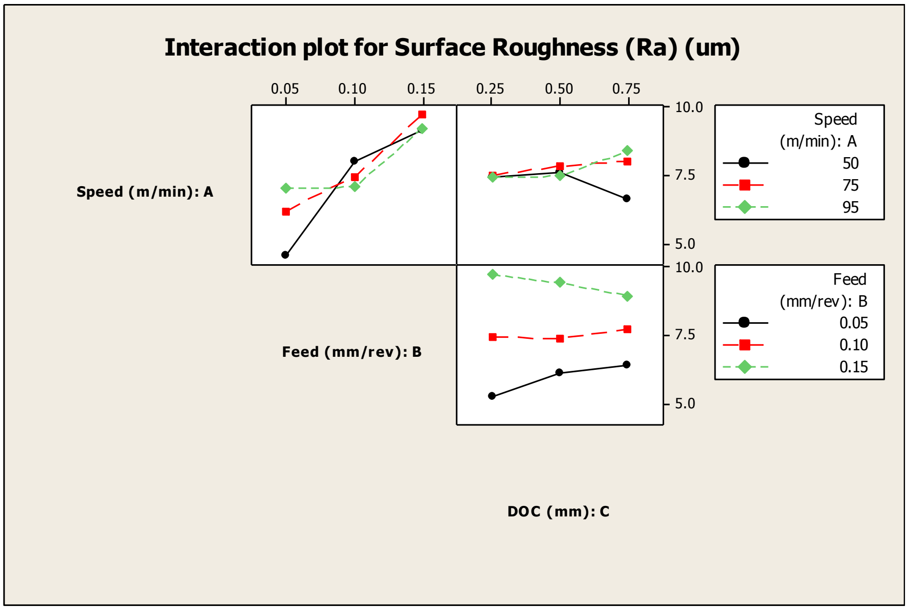

Figure - 6: Interaction Plot for Surface Roughness R_a(µm)

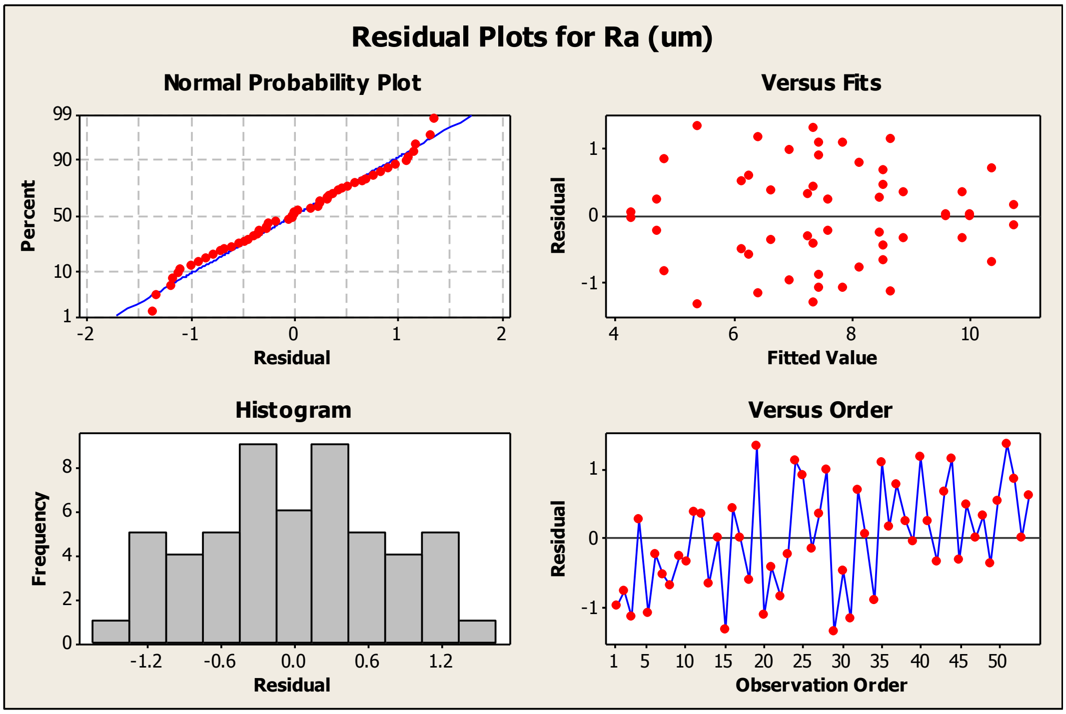

Figure - 7: Residual Plot for Surface Roughness R_a (µm)

The regression analysis was carried out to study the influence of cutting parameters on surface roughness and develop the regression model with interaction effects (Table 6). The model is adequately a good fit (R-square = 79.4%; R-square adjusted = 76.3%). The regression equation is as follows. It is interesting to note that all the cutting parameters as well as the interaction effects as indicated in the table 6 seem to be significantly influencing the surface roughness.

Ra (µm) = - 1.86 + 0.0743 *Speed + 110 *Feed + 5.48* depth of cut - 0.116* speed*feed - 60.1* feed*depth of cut + 0.0930* speed*feed*depth of cut +/- €

Where, € = regression error

Table - 6: Regression Analysis (Surface Roughness)

Predictor	Coef	SE Coef	T	P
Constant	-1.86	1.89	-0.98	0.33
Speed	0.074	0.03	2.83	0.01
Feed	110.42	19.49	5.66	0.00
DOC	5.48	2.39	2.29	0.026
Speed*Feed	-0.12	0.04	-3.32	0.002
Feed*DOC	-60.14	19.28	-3.12	0.003
Speed*Feed*DOC	0.09	0.04	2.21	0.032
S = 2.98097 R-Sq = 79.4% R-Sq(adj) = 76.3%				

5. Discussions and conclusions

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. Depth of cut has a significant influence on cutting force, but has an insignificant influence on surface roughness. The interaction of feed and depth of cut and the interaction of all the three cutting parameters have significant influence on cutting force, whereas, none of the interaction effects are having significant influence on the surface roughness produced. Hence, in the turning process optimization with respect to power consumption, the focus should be on choosing an appropriate combination of feed rate (< 0.06 mm/rev) and depth of cut (<0.15 mm). 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.

The surface roughness is a very important parameter as indicated before because it has bearing on several other usage related issues of the component. The regression model has made certain key revelation in terms of the influence of cutting parameters, which has not been revealed in the analysis of variance. The regression model with the P values indicated that the three cutting parameters and the two level interaction of speed & feed and feed & depth of cut, as well as the third level interaction of all the three have significant influence on surface roughness. The most significant among all these is obviously the feed rate which is very much in agreement with the analysis of variance. This is anticipated as it is well known that for a given tool nose radius, the theoretical surface roughness (R_a=f^2/ (32×r)) is mainly a function of the feed rate [6].

While the results declared through this experimental work may be generalized to a considerable extent while working on hardened AISI 1050 steel using ceramic (KY1615) 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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