

On the application of response surface methodology for predicting and optimizing surface roughness and cutting forces in hard turning by PVD coated insert

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ABSTRACT

This paper focuses on the exploitation of the response surface methodology (RSM) to determine optimum cutting conditions leading to minimum surface roughness and cutting force components. The technique of RSM helps to create an efficient statistical model for studying the evolution of surface roughness and cutting forces according to cutting parameters: cutting speed, feed rate and depth of cut. For this purpose, turning tests of hardened steel alloy (AISI 4140) (56 HRC) were carried out using PVD – coated ceramic insert under different cutting conditions. The equations of surface roughness and cutting forces were achieved by using the experimental data and the technique of the analysis of variance (ANOVA). The obtained results are presented in terms of mean values and confidence levels. It is shown that feed rate and depth of cut are the most influential factors on surface roughness and cutting forces, respectively. In addition, it is underlined that the surface roughness is mainly related to the cutting speed, whereas depth of cut has the greatest effect on the evolution of cutting forces. The optimal machining parameters obtained in this study represent reductions about 6.88%, 3.65%, 19.05% in cutting force components (F_a , F_r , F_t), respectively. The latter are compared with the results of initial cutting parameters for machining AISI 4140 steel in the hard turning process.

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Nomenclature

V_c	: Cutting speed (m/min)
f	: Feed rate (mm/rev)
ap	: Depth of cut (mm)
R_a	: Arithmetic average of absolute roughness (μm)
F_a	: Feed force (N)
F_r	: Thrust force (N)
F_t	: Tangential cutting force (N)
X_i	: Coded machining parameters
a_{ii}	: Quadratic term
a_j	: Coefficients of linear terms
a_{ij}	: Cross-product terms

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ANOVA	: Analysis of variance
RSM	: Response surface methodology
DF	: Degrees of freedom
Seq SS	: Sequential sum of squares
Adj MS	: Adjusted mean squares
PC%	: Percentage contribution ratio (%)
R^2	: Correlation coefficient
α	: Clearance angle, degree
γ	: Rake angle, degree
λ	: Inclination angle, degree
χ_r	: Major cutting edge angle, degree

1. Introduction

The use of modern ceramic insert materials in machining is very attractive from industrial point of view because they retain high strength up to a temperature of 1200°C. Nevertheless, cutting inserts have poor reliability because they are brittle (Casto et al. 2000). To overcome the mentioned shortcoming, TiC, or TiN to aluminium oxide are added as a coat on the insert leading to an increase both in its thermal conductivity and thermal resistance. Therefore, coated tools have been used for machining various steel alloys and cast iron successfully. Physical Vapour Deposition (PVD) is one among used techniques for coating tools. Its use is growing although its usage relatively low compared to the Chemical Vapour Deposition (CVD) technique. During cutting process, coated tools ensure higher wear resistance, lower heat generation and lower cutting forces, thus enabling them to perform behaviour at higher cutting conditions than their uncoated counterparts (Koelsch, 1992; Sahin, 2003). Hard turning is generally performed by superior hard tools like CBN and ceramic. The benefits of hard turning are the cost reduction per product, the improvement of surface finish closer to grinding, the high productivity, the ability to cut complex parts by single setup, the less costly equipment and the environment friendly dry cutting. Due to the development of PCBN cutting tools (commercially available in the mid-1970s) and advanced ceramic grades, the turning of steels with hardness values exceeding 50 HRC has been replaced extensively and successively the costly grinding operations Lalwani et al. (2008). The evolution of cutting force is considered, among others as an important technological output helping to control the machining process. It is the essential criterion for the evaluation of the necessary power machining (choice of the electric motor). It is also used for dimensioning of machine tool components and tool body. Moreover, this output influences machining system stability. In hard turning, cutting forces have been found to be affected by a number of factors such as depth of cut, feed rate, cutting speed, cutting time, workpiece hardness, etc. The response surface methodology (RSM) is a collection of mathematical and statistical procedures that are useful for modeling and analysing problems in which response optimization is affected by several variables Montgomery (2011). Various investigations have been carried out to study the performance of coated carbide insert, ceramic and cubic boron nitride (CBN) tools during machining of hard materials. Hessainia al. (2013) applied RSM to investigate the effect of cutting parameters and tool vibrations on surface roughness in hard turning of AISI 4140 with CC650 tool. Results show how much the surface roughness is highly influenced by feed rate variation. Suresh et al. (2002) focused their study on machining mild steel and TiN-coated tungsten carbide (CNMG) cutting tools for developing a surface roughness prediction model using RSM. Genetic algorithms (GAs) were also used to optimize the objective function and compared with RSM results. It was observed that GA program provided minimum and maximum values of surface roughness and their corresponded optimal machining conditions. Asiltürk and Akkus (2011) carried out hard turning experiment on hardened AISI 4140 steel (51 HRC) with coated carbide insert using Taguchi orthogonal array for surface roughness. Results of this study indicate that the feed rate has the most significant effect on the roughness Ra and Rz. In addition, the effects of two factor interactions of the feed rate cutting speed and depth of cut, cutting speed appear to be significant. However, other machinability characteristics like tool wear and tool life,

cutting force, chip morphology and cutting temperature have not been considered for study and which are essential for hard turning study. Luo et al. (1999) have investigated the relationship between hardness and cutting forces during turning AISI 4340 steel hardened from 29 to 57 HRC using mixed alumina tools. The results suggest that an increase of 48% in hardness leads to an increase in cutting forces from 30% to 80%. It is reported that for work material hardness values between 30 and 50 HRC, continuous chips were formed and the cutting force components were reduced. However, when the work piece hardness increased above 50 HRC, segmented chips were observed and the cutting force showed a sudden increase. Davim and Figueira (2007) investigated the machinability of AISI D2 tool steel using experimental and statistical techniques. Hard turning operation was performed on material having hardness of 60 HRC. The tests were conducted by using cutting speed, feed rate and time as main parameters. The influence of cutting parameters on the flank wear evolution, specific cutting force and surface roughness variations on machinability evaluation in turning with ceramic tools using ANOVA was presented. Yallese et al. (2009) have experimentally investigated the behavior of CBN tools during hard turning of AISI 52 100 tempered steel. The surface quality obtained with the CBN tool was found to be significantly improved than grinding. A relationship between flank wear and surface roughness was also established based on an extensive experimental data. Neseli et al. (2011) exploited RSM to optimize the effect of tool geometry parameters on surface roughness in the case of the hard turning of AISI 1040 with P25 tool. Park (2002) observed that the radial force is the largest force component regardless the grade of the insert used, i.e. PCBN or ceramic during turning hardened steel in dry conditions. The specific cutting energy in the case of the hard turning is found to be smaller than in grinding. Cutting force and surface roughness were found to be smaller when cutting with PCBN tools compared to ceramic ones under similar cutting conditions. Ozel et al. (2005) conducted a set of ANOVA and performed a detailed experimental investigation on the surface roughness and cutting forces in the finish hard turning of AISI H13 steel. Their results indicated that the effects of workpiece hardness, cutting edge geometry, feed rate and cutting speed on the surface roughness are statistically significant. Davim and Figueira (2007) performed experimental investigations on AISI D2 cold work tool steel (60 HRC) using ceramic tools composed approximately of 70% Al_2O_3 and 30% TiC in surface finish operations. A combined technique using an orthogonal array (OA) and analysis of variance (ANOVA) was employed in their study. The test results showed the possibility that to achieve surface roughness levels as low as $Ra < 0,8 \mu m$ with an appropriate choice of cutting parameters that eliminated cylindrical grinding. Sahoo and Sahoo (2011) conducted hard turning of AISI 4340 steel (47 HRC) using multilayer ZrCN coated carbide insert and developed mathematical model for surface roughness and flank wear. The optimized process parameter for multiple performance characteristics has been obtained using grey based Taguchi method. Mathematical model output concluded that the RSM models proposed are statistically significant and adequate because of their R^2 value. Lima et al. (2005) evaluated the machinability of hardened AISI 4340 and D2 grade steels at different levels of hardness by using various cutting tool materials. The AISI 4340 steels were hardened to 42 and 48 HRC and then turned by using coated carbide and CBN inserts. The higher cutting forces were recorded when AISI 4340 steel was turned using low feed rates and depth of cut. Also, lower surface roughness values were observed for softer workpiece materials when increasing cutting speed and they are deteriorated with high feed rate values. The influence of cutting speed, feed rate and machining time on machinability aspects such as specific cutting force, surface roughness and tool wear in AISI D2 cold work tool steel hard turning was studied by Gaitonde et al. (2009, 2011) using RSM and ANN based models. Vikram Kumar et al. (2008) compared the performance of TiCN and TiAlN coated tools in machining AISI 4340 hardened steel under dry, wet and minimum fluid application conditions. Minimum fluid application yields better result compared to wet and dry machining. However, high performance of the TiAlN coated tool regarding wear resistance and surface finish. To investigate potentials of applications in hard turning, (Lima et al. 2007) have carried out turning operations using coated carbide tools on AISI 4340 steel hardened from 250 to 525 HV. It was concluded that, the cutting force increases with the work material hardness. However, it decreases slightly as the work piece hardness increased from 250 to 345 HV. More et al. (2006) have experimentally investigated the effects of cutting speed and feed rate on tool wear, surface roughness and cutting forces when turning

of AISI 4340 hardened steel using CBN-TiN-coated carbide inserts. In addition, machining cost analysis was also performed in economic conditions to compare CBN-TiN-coated and PCBN inserts. Aneiro et al. (2008) have studied the turning of hardened steel using TiCN/Al₂O₃/TiN coated carbide tool and PCBN tools during turning of hardened steel. They observed that high tool life could be achieved using PCBN tool, but their cost is twice the coated carbide one. Machining medium hardened steels with TiCN/Al₂O₃/TiN inserts tend to be more productive. The relatively good performance of coated carbide tools in machining hardened steel relied on the coating combination of layers. Chou et al. (2002), Thiele et al. (2000) and Ozel et al. (2005) explained the effects of various factors affecting cutting forces, surface roughness, tool wear and surface integrity in hard turning of various grades of steels using CBN tools. Chou and song (2004) concluded that better surface finish could be achieved using a large tool nose radius on finish turning of AISI 52 100 bearing steel using alumina titanium-carbide tools but generates deeper white layers. Benga and Abrao (2003) and Kumar et al. (2003) observed superior surface quality in turning of hardened steel components using alumina TiC ceramic tools. In this global framework, the aim of the present study is to optimize and predicted surface roughness and cutting force components in the case of the hard turning by PVD coated ceramic insert of AISI 4140 steel alloy (56 HRC) based on statistical method. Various cutting conditions (cutting speed, feed rate, and depth of cut) were adopted for this study and response surface methodology and 3³ factorial design of experiment, quadratic model have been developed with 95% confidence level.

2. Experimental procedure

2.1 Equipment and materials

The experimental work was carried out on a lathe (Tos TRENCIN; model SN 40C, spindle power 6.6 kW). The work material used during the turning tests was hardened and tempered to 56 HRC steel alloy AISI 4140 (70 mm diameter and 370 mm length). Its Chemical composition is given in Table 1. Coated ceramic insert with an ISO designation of SNGA120408T01020 (sandvik, Grade CC6050) was used in the experimental work with clamp-type PSBN25×25K12 tool holder, yielding to the following principal angle: cutting edge angle $\chi_r = 75^\circ$, negative inclination angle $\lambda = -6^\circ$, negative rake angle $\gamma = -6^\circ$, clearance angle $\alpha = 6^\circ$ and tool nose radius $R_\epsilon = 0.8 \text{ mm}$ (Sandvik, 2009). The tests were carried in dry cutting conditions.

Table 1

Chemical composition of AISI 4140 steel.

Composition	C	Si	Mn	S	P	Ni	Cu	Cr	V	Mo	Fe
%	0.42	0.025	0.08	0.018	0.013	0.021	0.022	1.08	0.004	0.209	96.95

Three levels were specified for each process parameter as given in Table 2. The factor levels were chosen within the intervals recommended by the cutting tool manufacturer (Kennametal, 2000).

Table 2

Attribution of the levels to the factors.

Level	Cutting speed, V_c (m/min)	Feed rate, f (mm/rev)	Depth of cut, ap (mm)
1 (low)	90	0.08	0.15
2 (medium)	120	0.12	0.30
3 (high)	180	0.16	0.45

The cutting forces which are feed force (F_a), thrust force (F_r) and tangential force (F_t) were recorded using a standard quartz dynamometer (Kistler 9257B) allowing measurements from -5 to 5 KN. The measurement chain also included a charge amplifier (Kistler 5019B130), data acquisition hardware (A/D 2855A3) and graphical programming environment (DYNOWARE 2825A1-1) for data analysis and visualization. Each test for measuring the turning forces lasted for 5 s and an acquisition rate of 500

Hz was employed. The experimental setup is shown in Fig. 1; the measurements of arithmetic surface roughness (R_a) for each cutting condition were obtained from a Surftest 201 Mitutoyo roughnessmeter with a cut-off length of 0.8 mm and sampling length of 5 mm. The measurements were repeated at three equally spaced locations around the circumference of the workpiece and the result is an average of these values for a given machining pass.

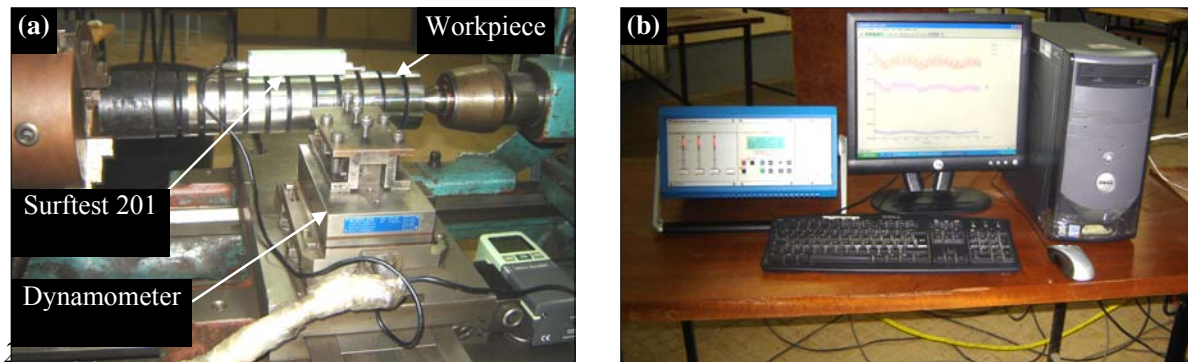


Fig.1. (a) Experimental setup with measurement of the cutting forces by piezoelectric dynamometer and surface roughness, and (b) charge amplifiers and PC based data acquisition system.

For the elaboration of experiments plan the method of Taguchi for three factors at three levels was used by levels the values taken by the factors were averaged. Table 2 indicates the factors to be studied and the assignment of the corresponding levels. The array chosen was the $L_{27}(3^{13})$ which have 27 rows corresponding to the number of tests (26 degrees of freedom) with 13 columns at three levels as shown in Table 3 (Ross, 1988). The factors and the interactions are assigned to the columns.

Table 3

Orthogonal array $L_{27}(3^{13})$ of Taguchi (33).

$L_{27}(3^{13})$	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

The plan of experiments is made of 27 tests (array rows) in which the first column was assigned to the cutting speed (V_c), the second column to the feed rate (f), the fifth column to the depth of cut (ap) and the remaining columns to the interactions. A randomized schedule of runs was created using the design

of experiment shown in Table 4. The response surface methodology (RSM) is a procedure for determining the relationship between the independent process parameters with the desired response and exploring the effect of these parameters on responses, including six steps (Gained et al., 2009). The latter, help to (1) define the independent input variables and the desired responses with the design constants, (2) adopt an experimental design plan, (3) perform regression analysis with the quadratic model of RSM, (4) calculate the statistical analysis of variance (ANOVA) for the independent input variables in order to find which parameter significantly affects the desired response, then, (5) determine the situation of the quadratic model of RSM and decide whether the model of RSM needs screening variables or not and finally, (6) optimize and conduct confirmation experiment and verify the predicted performance characteristics.

Table 4
Design layout and experimental results.

Run	Coded factors			Actual factors			Response variables			
	X_1	X_2	X_3	V_c (m/min)	f (mm/rev)	ap (mm)/ f	Ra (μ m)	Fa (N)	Fr (N)	Ft (N)
1	-1	-1	1	90	0.08	0.45	0.35	134.47	223.2	169.8
2	1	0	1	180	0.12	0.45	0.38	110.91	179.04	137.45
3	1	0	0	90	0.12	0.30	0.46	89.39	197.95	139.90
4	-1	0	-1	90	0.12	0.15	0.44	36.46	140.86	73.87
5	-1	-1	-1	90	0.08	0.15	0.32	34	130.08	64.14
6	1	1	0	180	0.16	0.30	0.47	72.02	206.47	143.52
7	1	-1	0	180	0.08	0.30	0.24	59.43	153.16	88.06
8	0	-1	0	120	0.08	0.30	0.31	70.02	174.88	118.39
9	-1	1	1	90	0.16	0.45	0.63	146.38	278.41	219.13
10	0	-1	1	120	0.08	0.45	0.32	110.01	203.18	152.07
11	-1	1	-1	90	0.16	0.15	0.60	38.78	156.37	100.58
12	0	1	0	120	0.16	0.30	0.50	79.88	207.49	157.92
13	1	-1	1	180	0.08	0.45	0.26	88.8	165.58	98.15
14	1	-1	-1	180	0.08	0.15	0.23	32.08	120.97	43.03
15	1	1	-1	180	0.16	0.15	0.45	38.81	142.18	78.84
16	1	0	-1	180	0.12	0.15	0.34	31.55	120.97	41.8
17	-1	0	1	90	0.12	0.45	0.47	141.94	238.14	215.15
18	0	0	0	120	0.12	0.30	0.40	78.39	183.05	129.65
19	0	-1	-1	120	0.08	0.15	0.26	33.09	123.62	52.06
20	1	0	0	180	0.12	0.30	0.37	68.59	167.67	110.53
21	1	1	1	180	0.16	0.45	0.49	120.84	274.23	179.05
22	0	0	1	120	0.12	0.45	0.42	126.42	221.16	202.84
23	0	1	-1	120	0.16	0.15	0.47	39.68	145.37	89.49
24	-1	-1	0	90	0.08	0.30	0.34	70.5	179.65	124.31
25	0	0	-1	120	0.12	0.15	0.37	36.44	133.63	73.08
26	0	1	1	120	0.16	0.45	0.53	136.35	278.17	210.92
27	-1	1	0	90	0.16	0.30	0.62	94.07	214.85	170.44

In the current study, the relationship between (cutting speed (V_c), feed rate (f) and depth of cut (ap)) and the outputs named Y, defines machinability of AISI 4140 (56 HRC) in terms of cutting forces and surface roughness. This relationship is given by:

$$Y = F(V_c, f, ap) + e_{ij} \quad (1)$$

where Y is the desired machinability aspect and F is a function proposed by using a non-linear quadratic mathematical model, which is suitable for studying the interaction effects of process parameters on machinability characteristics. In the present work, the RMS based second order mathematical model is given by:

$$Y = a_o + \sum_{i=1}^3 a_i X_i + \sum_{i=1}^3 a_{ii} X_i^2 + \sum_{i \neq j}^3 a_{ij} X_i X_j \quad (2)$$

where a_o is constant, a_i , a_{ii} , and a_{ij} represent the coefficients of linear, quadratic and cross product terms, respectively. X_i reveals the coded variables that correspond to the studied machining parameters. The coded variables $X_{i,i=1,2,3}$ are obtained from the following transformation equations.

$$X_1 = \frac{Vc - Vco}{\Delta Vc} \quad (3)$$

$$X_2 = \frac{f - fo}{\Delta f} \quad (4)$$

$$X_3 = \frac{ap - apo}{\Delta ap} \quad (5)$$

where X_1 , X_2 and X_3 are the coded values of parameters Vc , f and ap respectively. Vco , fo and apo are factors at zero level. ΔVc , Δf and Δap are the increment values of Vc , f , and ap , respectively.

3. Analysis and the discussion of experimental results

The plan of tests was developed for assessing the influence of the cutting speed (Vc), feed rate (f) and depth of cut (ap) on both the surface roughness (Ra) and cutting force components such as feed force (Fa), thrust force (Fr) and tangential cutting force (Ft). The first phase was concerned with the ANOVA and the effect of the factors and of the interactions. The second phase allowed to obtain correlations between the process parameters (quadratic regression). Afterwards, the results were through optimized. Table 4 illustrates the experimental results for surface roughness (Ra) and feed force (Fa), thrust force (Fr) and tangential cutting force (Ft).

3.1. Analysis of variance

ANOVA technique can be useful for determining influence of any given input parameters from a series of experimental results by design of experiments for machining process and it can be used to interpret experimental data. The obtained results are analyzed by statistical analysis software (Minitab-16) which is widely used in many engineering applications. The ANOVA table consists of a sum of squares and degrees of freedom. The mean square is the ratio of sum of squares to degrees of freedom and F ratio is the mean square ratio to the mean square of the experimental error. The results of the ANOVA with the surface roughness and cutting forces are shown in Tables 5 and 6 (a , b , and c), respectively. This analysis was carried out for a significance level of $\alpha = 0.05$, i. e. for a confidence level of 95% (Ross, 1988). Tables 5 and 6 (a , b , and c) show the P – values, that is, the realized significance levels, associated with the F- tests for each source of variation. The sources with the P – value less than 0.05 are considered to have a statistically significant contribution to the performance measures (Gained et al. 2009). Also the last columns of the tables show the percent contribution of each source to the total variation indicating the degree of influence on the results. The greater the percentage contribution, the higher the factor influence on the performance measures.

Table 5

Analysis of variance for (Ra).

Source	DF	SeqSS	AdjMS	F.Value	Prob > F	Cont%
Vc	1	0.050060	0.007511	25.59	0.000	15.47
f	1	0.252050	0.001908	6.50	0.021	77.92
ap	1	0.007606	0.000331	1.13	0.303	2.35
$Vc \times f$	1	0.001419	0.001419	4.39	0.051	0.43
$Vc \times ap$	1	0.000002	0.000002	0.01	0.942	0.00
$f \times ap$	1	0.000008	0.000008	0.03	0.868	0.00
Vc^2	1	0.007163	0.007163	24.40	0.000	2.21
f^2	1	0.000150	0.000150	0.51	0.484	0.04
ap^2	1	0.000150	0.000150	0.51	0.484	0.04
Error	17	0.004990	0.000294			1.54
Total	26	0.323467				100

3.1.1. Effect of cutting parameters on surface roughness

According to Table 5, the feed rate was found to be the major factor affecting the surface roughness (77.92%), this results is in a concordance with those published in (Hessainia al. 2013), (Aslan, 2005) and (Yallese et al., 2005). The cutting speed and depth of cut factors affect the surface roughness by 15.47% and 2.35%, respectively. It can be revealed that lower surface roughness values are obtained at higher cutting speeds due to lower forces generated. At high cutting speed, an improvement in surface finish was obtained since less heat was dissipated to the workpiece. It is known that the amount of heat generation increases with increase in feed rate, because the cutting tool has to remove more volume of material from the workpiece (Davim, 2011). The plastic deformation of the work piece is proportional to the amount of heat generation in the work piece and promotes roughness on the work piece surface. Depth of cut parameter has a very less effect compared to that of the feed rate. This is due to the increased length of contact between the tool and the workpiece. This improves the conditions of heat flow from the cutting zone. Similar results were also observed by (Palanikumar, 2007). From interaction plot Fig. 2a it can be observed on the one hand for a given cutting speed, the surface roughness sharply increases with increase in feed rate. On the hand, surface roughness has a tendency to be reduced with an increase in cutting speed at constant feed rate. The minimal surface roughness results with the combination of low feed rate and high cutting speed. Fig. 2b indicates that the depth of cut is low; the surface roughness is highly sensitive to cutting speed. An increase in the latter sharply reduces the surface roughness. Nevertheless, this reduction becomes smallest with higher values of depth of cut which usually does not much influence the surface roughness. Fig. 2c indicates that for a given depth of cut, the surface roughness increases with the increase in feed rate, whereas depth of cut has less effect on surface roughness. It revealed that a combination of higher cutting speed along with lower feed rate and depth of cut is necessary for minimizing the surface roughness. An improvement of surface finish Ra of $0.23 \mu\text{m}$ was recorded at higher cutting speed of 180 m/min , feed rate of 0.08 mm/rev and depth of cut of 0.15 mm .

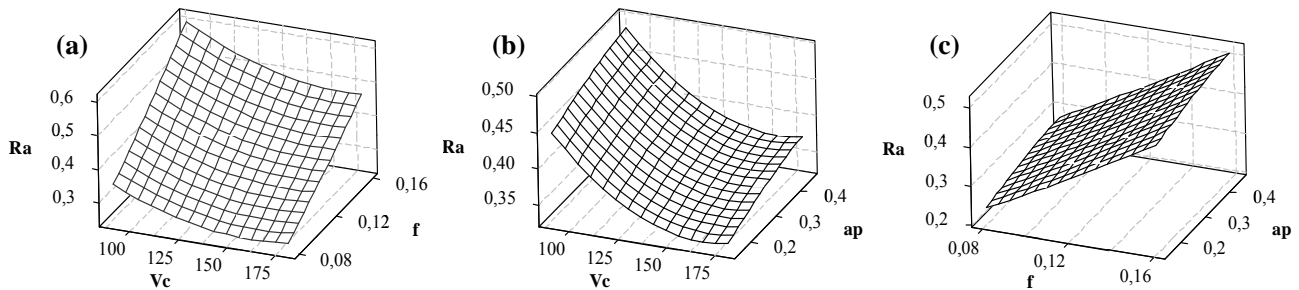


Fig.2. (a) 3D surface plots for interaction effects of feed rate and cutting speed, (b) depth of cut and cutting speed, and (c) depth of cut and feed rate on surface roughness

3.1.2. Effect of cutting parameters on cutting force components

Tables 6(a, b and c) shows the results of the ANOVA for feed force (F_a), thrust force (F_r) and tangential force (F_t). It can be found that depth of cut is the most significant cutting parameter for affecting cutting forces (F_a , F_r and F_t) (90.22%, 67.64% and 69.443%), respectively. The cutting speed affects the cutting forces (F_a , F_r and F_t) by (3.66%, 5.01%, and 10.37%), respectively. The feed rate affects the cutting forces (F_a , F_r and F_t) by (2.61%, 17.36% and 14.60%), respectively. In this study, the factors and the interactions present a statistical significance Test $F > P_{\alpha} = 5\%$ except for the interaction $V_c \times ap$ and $f \times ap$ for Ra , the interaction V_c^2 for F_r and effect of V_c , f , and the interaction f^2 for F_t . Notice that the error associated to the Tables ANOVA for the Ra was approximately 1.54%, for the F_a was approximately 0.62%, for the F_r was approximately 2.52% and for F_t was 2.02%. The interaction [for Ra (f^2 , ap^2 , $V_c \times f$, $V_c \times ap$, $f \times ap$), for F_a (V_c^2 , f^2 , ap^2 , $V_c \times f$, $f \times ap$), for F_r (V_c^2 , f^2 , ap^2 , $V_c \times f$, $V_c \times ap$) and for F_t (V_c^2 , f^2 , ap^2 , $V_c \times f$, $V_c \times ap$, $f \times ap$)] do not present a physical significance P

(percentage of contribution) < error associated. As seen from the interaction plots in Fig. 3, 4, 5, (a and b) for a given cutting speed, the feed force, thrust force and tangential force sharply increases with the increase in feed rate or depth of cut. The component forces F_a , F_r and F_t are highly sensitive to depth of cut, as shown in Fig. 3, 4, 5, (c). From the above discussions it can be manifest that the precited forces can be minimized by employing lower valuer of f and ap and with higher V_c . Also it can be underlined F_r is usually the largest force among the other ones. The tangential cutting force component F_t is the middle force and F_a is the smallest one.

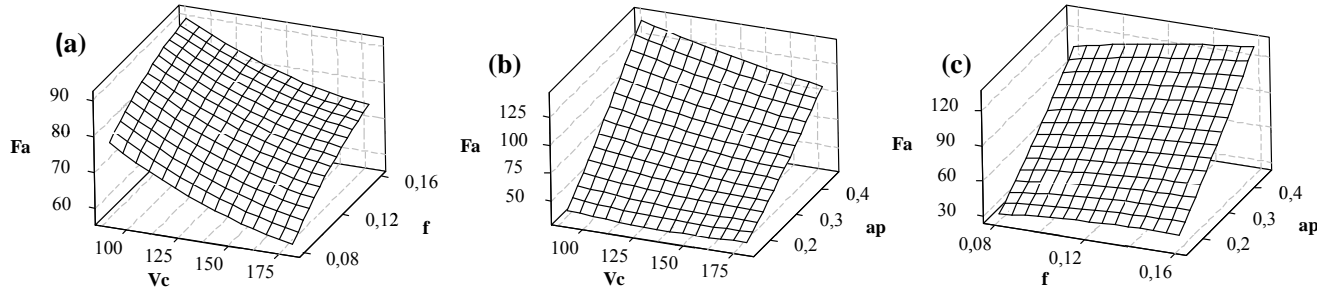


Fig.3. (a) 3D surface plots for interaction effects of feed rate and cutting speed, (b) depth of cut and cutting speed, and (c) depth of cut and feed rate on feed force

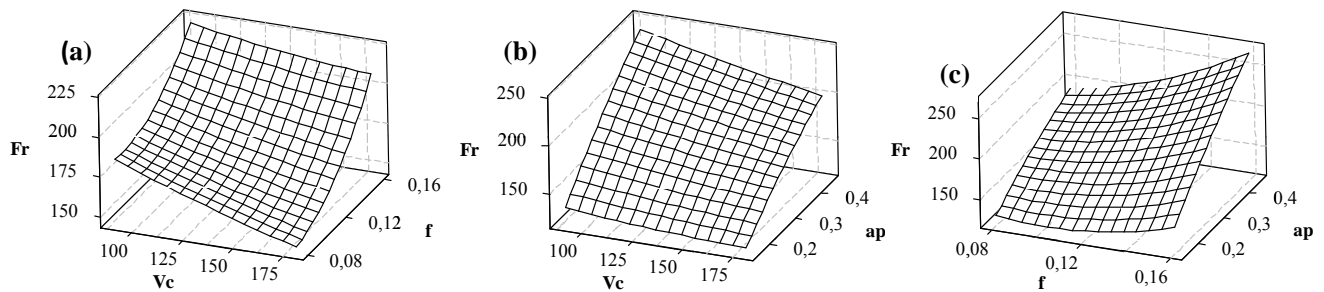


Fig.4. (a) 3D surface plots for interaction effects of feed rate and cutting speed, (b) depth of cut and cutting speed, and (c) depth of cut and feed rate on thrust force

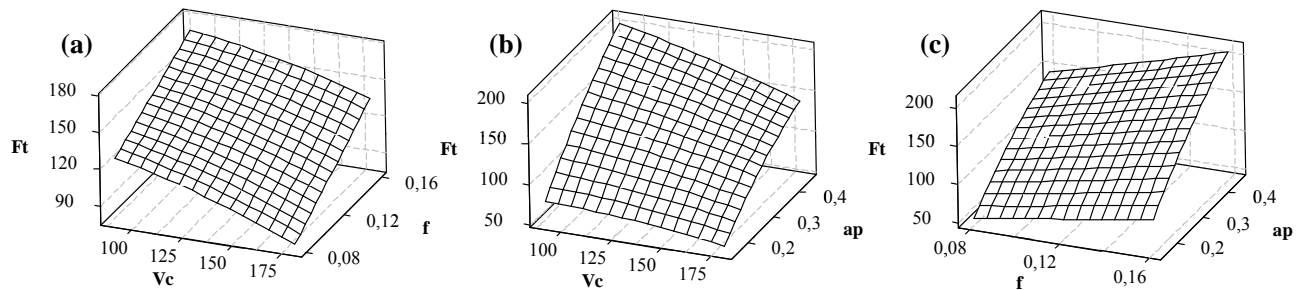


Fig.5. (a) 3D surface plots for interaction effects of feed rate and cutting speed, (b) depth of cut and cutting speed, and (c) depth of cut and feed rate on tangential force

Using ANOVA to make this comparison requires several assumptions to be satisfied. The assumptions underlying the analysis of variance tell the residuals are determined by evaluating the following equation (Zarepour et al., 2006).

$$e_{ij} = y_{ij} - \hat{y}_{ij} \quad (6)$$

where e_{ij} is the residual, y_{ij} is the corresponding observation of the runs, and \hat{y}_{ij} is the fitted value. A check of the normality assumption may be made by constructing the normal probability plot of the residuals. If the underlying error distribution is normal, this plot will resemble a straight line Fig.6 (a, b, c and d). Since the p-value is larger than 0.05, it is concluded that normality assumption is valid. The other two assumptions are shown valid by means of plot of residuals versus fitted values. This plot is illustrated in Fig.7 (a, b, c and d). The structure less distribution of dots above and below the abscissa (fitted values) shows that the errors are independently distributed and the variance is constant. For more information the reader can refer to the reference refer to (Montgomery & Runger, 2003).

Table 6

Analysis of variance for cutting force components: (a) F_a , (b) F_r and (c) F_t .

Source	DF	SeqSS	AdjMS	F.Value	Prob > F	Cont%
(a) Analysis of variance for (F_a).						
V_c	1	1425.6	18.7	1.32	0.267	3.66
f	1	1018.7	11.9	0.84	0.373	2.61
ap	1	35132.8	339.8	23.90	0.000	90.22
$V_c \times f$	1	13.3	13.3	0.94	0.346	0.03
$V_c \times ap$	1	743.3	743.3	50.95	0.000	1.90
$f \times ap$	1	227.0	227.0	15.97	0.000	0.58
V_c^2	1	33.7	33.7	2.37	0.142	0.08
f^2	1	29.6	29.6	2.08	0.167	0.07
ap^2	1	91.9	91.9	6.46	0.021	0.23
Error	17	214.7	14.2			0.62
Total	26	38938.5				100
(b) Analysis of variance for (F_r).						
V_c	1	2957.0	72.4	0.83	0.376	5.01
f	1	10235.0	1196.0	13.64	0.002	17.36
ap	1	39861.7	493.3	5.63	0.030	67.64
$V_c \times f$	1	445.6	445.6	4.63	0.046	0.75
$V_c \times ap$	1	561.0	561.0	6.40	0.022	0.95
$f \times ap$	1	2397.0	2397.0	27.34	0.000	4.06
V_c^2	1	11.2	11.2	0.13	0.725	0.01
f^2	1	839.5	839.5	9.58	0.007	1.42
ap^2	1	167.8	167.8	1.91	0.184	0.28
Error	17	1490.3	87.7			2.52
Total	26	58926.2				100
(c) Analysis of variance for (F_t).						
V_c	1	7727	13.7	0.15	0.699	10.37
f	1	10872.7	1.4	0.02	0.900	14.60
ap	1	51699.3	2408.6	27.12	0.000	69.44
$V_c \times f$	1	179.9	179.9	2.03	0.173	0.24
$V_c \times ap$	1	1334.1	1334.1	14.68	0.001	1.79
$f \times ap$	1	565.8	565.8	6.37	0.022	0.76
V_c^2	1	62.4	62.4	0.70	0.414	0.08
f^2	1	1.5	1.5	0.02	0.900	0.00
ap^2	1	522.5	522.5	5.88	0.027	0.70
Error	17	1509.7	88.8			2.02
Total	26	74444.9				100

3.2. Regression equations

According to (Montgomery & Runger, 2003), (Montgomery, 2000), the correlation between the factors and the performance measures were modeled by quadratic regressions. The models are reduced by eliminating terms with no significant effect on the responses. The estimated regression coefficients for surface roughness R_a and cutting forces F_a , F_r and F_t using data uncoded units are shown in Tables 7 and 8 (a, b, c).

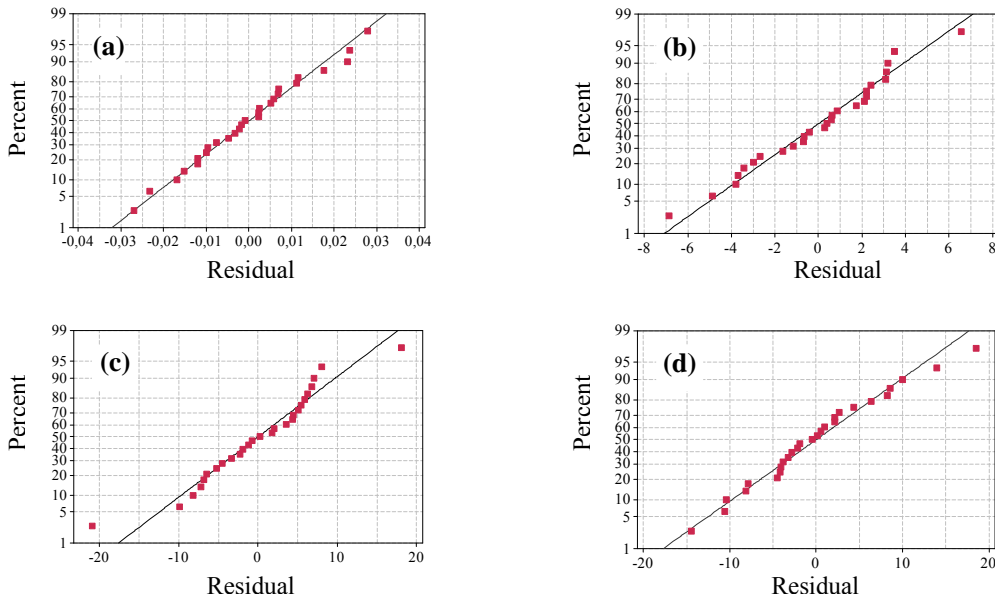


Fig.6. Normal probability plot of residuals for (a) *Ra* and for (b) *Fa*, (c) *Fr* and (d) *Ft* respectively

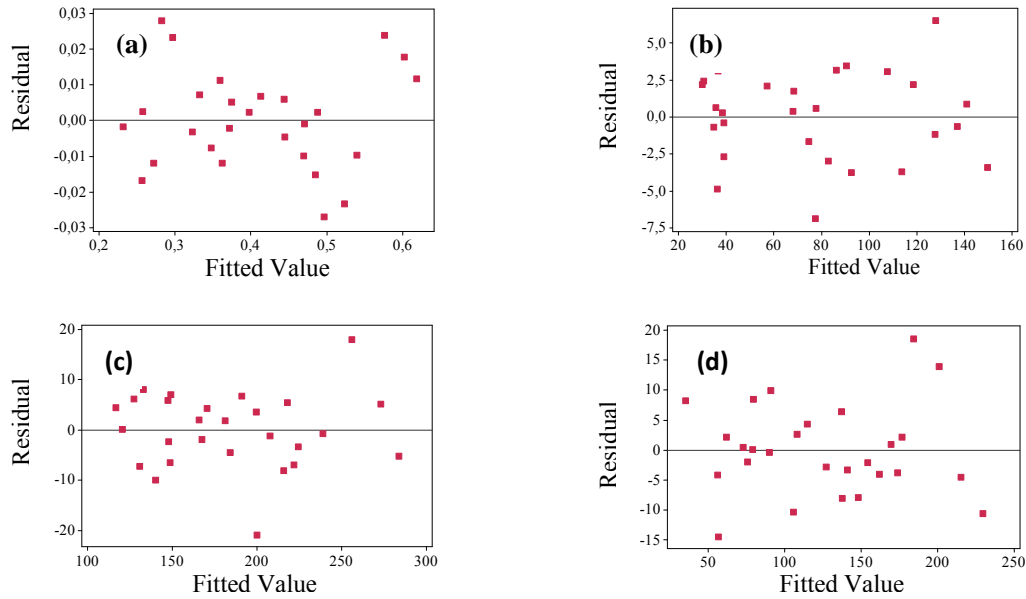


Fig.7. Plot of residuals vs. Fitted values for (a) *Ra*, and for (b) *Fa*, (c) *Fr* and (d) *Ft*, respectively

Table 7

Table of coefficients for regression analysis, Response *Ra*.

Predictor	Coefficient	SE coefficient	T	Prob
Constant	0.4455	0.1116	3.99	0.00
<i>Vc</i>	-0.00584	0.0011	-5.06	0.00
<i>f</i>	2.90179	1.138	2.55	0.00
<i>ap</i>	0.2468	0.2325	1.06	0.00
<i>Vc</i> ²	0.0000195	0.0000	4.94	0.00

The surface roughness (Ra) model is given below in Eq. (7) with a determination coefficient $R^2 = 98.5\%$; Adjusted R^2 was 97.5% .

$$Ra = 0.4455 - 5.84 \times 10^{-3} Vc + 2.90f + 2.4 \times 10^{-1} ap + 1.95 \times 10^{-5} Vc^2 \quad (7)$$

The feed force model (Fa) is given by Eq. (8) with a determination coefficient R^2 of 99.4% ; Adjusted R^2 was 99.1% .

Table 8

Table of coefficients for regression analysis, Response (a) Fa , (b) Fr , and (c) Ft .

Predictor	Coefficient	SE coefficient	T	Prob
(a) Table of coefficients for regression analysis (Fa)				
Constant	1.6501	24.56	0.07	0.00
Vc	-0.291	0.25	-1.15	0.00
f	250.13	51.16	4.89	0.00
ap	250.13	51.16	4.89	0.00
ap^2	173.90	68.41	2.54	0.02
$Vc \times ap$	-1.13	0.15	-7.14	0.00
$F \times ap$	724.86	181.4	4.00	0.00
(b) Table of coefficients for regression analysis (Fr)				
Constant	244.296	60.98	4.01	0.00
Vc	0.57	0.63	-0.91	0.00
f	-2297.17	621.9	-3.69	0.00
ap	301.37	127.0	2.37	0.00
$Vc \times f$	3.17	1.47	2.15	0.04
$Vc \times ap$	0.99	0.39	-2.53	0.02
$F \times ap$	2355.56	450.5	5.23	0.00
(c) Table of coefficients for regression analysis (Ft)				
Constant	-40.5591	24.56	0.07	0.00
Vc	0.249	0.25	-1.15	0.00
f	-77.26	250.4	0.91	0.00
ap	665.94	51.16	4.89	0.00
ap^2	-414.74	68.41	2.54	0.02
$Vc \times ap$	-1.51	0.15	-7.14	0.00
$F \times ap$	1144.44	181.4	4.00	0.02

$$Fa = 1.6501 - 2.91 \times 10^{-3} Vc + 228.93f + 250.13ap + 173.90ap^2 - 1.13Vc \times ap + 724.86f \times ap \quad (8)$$

The thrust force model (Fr) is given by Eq. (9) with a determination coefficient R^2 of 97.5% ; Adjusted R^2 was 96.1% .

$$Fr = 244.296 - 5.7 \times 10^{-1} Vc - 2297.17f + 301.37ap + 7393.06f^2 + 3.17Vc \times f - 9.9 \times 10^{-1} Vc \times ap + 2355.56f \times ap \quad (9)$$

The tangential force model (Ft) is given by Eq. (10) with a determination coefficient R^2 of 98% ; Adjusted R^2 was 96.9% .

$$Ft = 40.5591 + 2.4 \times 10^{-1} Vc - 77.26f + 665.94ap - 414.74ap^2 - 1.51Vc \times ap + 1144.44f \times ap \quad (10)$$

The use of the Hessian matrix proved that the objective function is convex and admits a global minimum. Example, for the surface roughness Ra we note that Ra is a convex function and it is assumed a minimum solution ($Vc = 91.5$ m/min, $f = 0.2$ mm/rev and $ap = 0.4$ mm). Fig.8 (a, b, c and d) also, show the predicted values of cutting forces and surface roughness form response surface equations (7 to 10) and the actual experimental values are reported in Table 4. The results of the comparison proves that predicted values of the surfaces roughness (Ra) and cutting force components (Fa , Fr and Ft) are very close to those readings recorded experimentally.

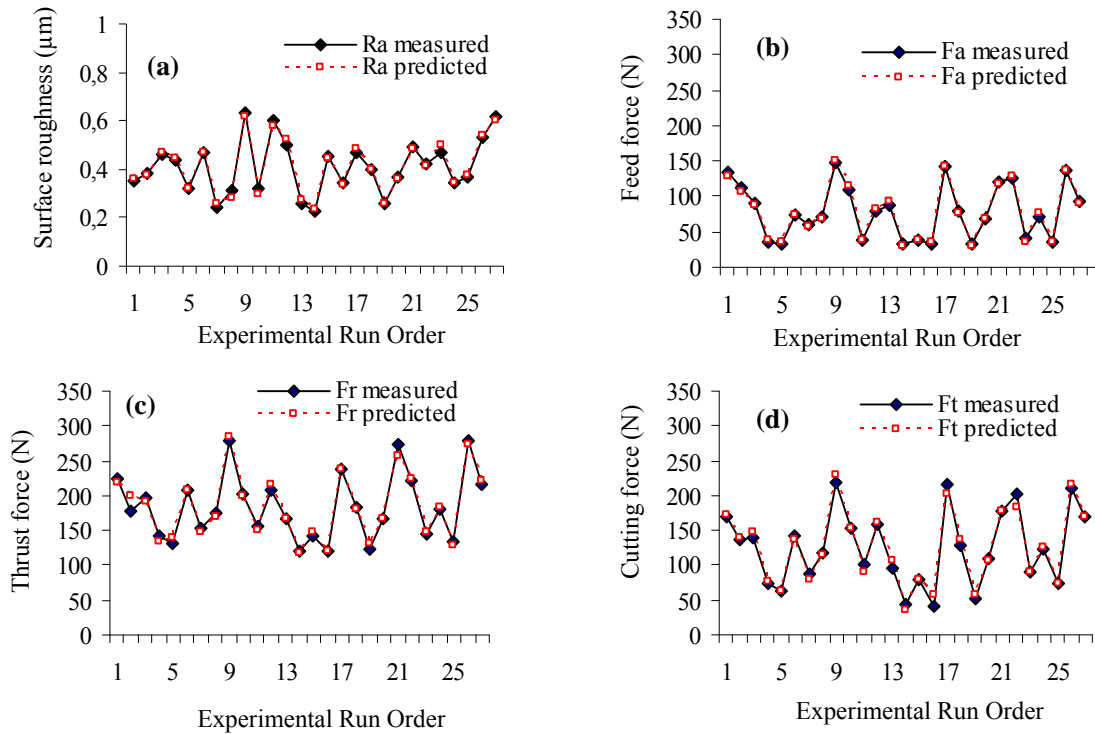


Fig.8. (a) The comparison between measured and predicted value of Ra and (b), (c), (d) comparison between measured and predicted value of Fa , Fr and Ft respectively

Table 9

ANOVA table for the fitted models (Ra).

Source	DF	Seq SS	Adj MS	F-Value	Prob > F	Remarks
Regression	9	0.318477	0.035386	120.56	< 0.000	Significant
Residual error	17	0.004990	0.000294			
Total	26	0.323467				
R^2					98.5 %	
R^2 adjusted					97.5 %	

Table 10

ANOVA table for the fitted models for cutting force components: (a) Fa , (b) Fr and (c) Ft .

Source	DF	Seq SS	Adj MS	F-Value	Prob > F	Remarks
(a) ANOVA table for the fitted models (Fa).						
Regression	9	3869.6	4299.7	302.48	< 0.000	Significant
Residual error	17	241.7	14.2			
Total	26	38938.5				
R^2					99.4%	
R^2 adjusted					99.1%	
(b) ANOVA table for the fitted models (Fr).						
Regression	9	57435.9	6381.8	72.80	< 0.000	Significant
Residual error	17	1490.3	87.7			
Total	26	58926.2				
R^2					97.5%	
R^2 adjusted					96.1 %	
(c) ANOVA table for the fitted models (Ft).						
Regression	9	72935.2	8103.9	91.25	< 0.000	Significant
Residual error	17	1509.7	88.8			
Total	26	74444.9				
R^2					98.0%	
R^2 adjusted					96.9%	

Analysis of variance was derived to examine the null hypothesis for regression that is presented in Tables 9-10. The result indicates that the estimated model by regression procedure is significant at α -level of 0.05.

4. Optimization of response

According to Hessainia et al. (20013), Neseli et al. (2011), one of the most important aims of experiments related to manufacturing is to achieve the desired surface roughness and cutting force components with the optimal cutting parameters. To attain this end, the exploitation of the RSM optimization seems to be a helpful technique. Here, the goal is to minimize surface roughness (Ra) and cutting forces (Fa , Fr and Ft), the parameter ranges defined for the optimization processes are summarized in Table 11.

Table11

Goals and parameter ranges for optimization of cutting conditions.

Condition	Goal	Lower limit	Upper limit
Cutting speed, Vc	is in range	90	180
Feed rate, f	is in range	0.08	0.16
Depth of cut, ap	is in range	0.15	0.45
Ra (μm)	minimize	0.23	0.63
Fa (N)	minimize	32.08	146.38
Fr (N)	minimize	120.97	278.41
Ft (N)	minimize	43.03	219.13

To resolve this type of parameter design problem, an objective function, $F(x)$, is defined as follows (Myers & Montgomery, 2002):

$$DF = \left(\prod_{i=1}^n d_i^{w_i} \right)^{\frac{1}{\sum_{j=1}^n w_j}} \quad (11)$$

$$F(x) = -DF$$

where d_i is the desirability defined for the i th targeted output and w_i is the weighting of d_i . For various goals of each targeted output, the desirability, d_i , is defined in different forms. If a goal is to reach a specific value of T_i , the desirability d_i is:

$$d_i = 0 \text{ if } Y_i \leq Low_i$$

$$d_i = \left[\frac{Y_i - Low_i}{T_i - Low_i} \right] \text{ if } Low_i \leq Y_i \leq T_i \quad (12)$$

$$d_i = \left[\frac{Y_i - High_i}{T_i - High_i} \right] \text{ if } T_i \leq Y_i \leq High_i$$

$$d_i = 0 \text{ if } Y_i \geq High_i$$

For a goal to find a maximum, the desirability is shown as follows:

$$d_i = 0 \text{ if } Y_i \leq Low_i$$

$$d_i = \left[\frac{Y_i - Low_i}{High_i - Low_i} \right] \text{ if } Low_i \leq Y_i \leq High_i \quad (13)$$

$$d_i = 1 \text{ if } Y_i \geq High_i$$

For a goal to search for a minimum, the desirability can be defined by the following formulas:

$$d_i = 1 \text{ if } Y_i \leq Low_i$$

$$d_i = \left[\frac{High_i - Y_i}{High_i - Low_i} \right] \text{ if } Low_i \leq Y_i \leq High_i \tag{14}$$

$$d_i = 0 \text{ if } Y_i \geq High_i$$

where the Y_i is the found value of the i th output during optimization processes; the Low_i and the $High_i$ are, respectively, the minimum and the maximum values of the experimental data for the i th output. In Eq. (11), w_i is set to one since the d_i is equally important in this study. The DF is a combined desirability function (Myers & Montgomery, 2002), and the objective is to choose an optimal setting that maximizes a combined desirability function DF , i.e., minimizes $F(x)$.

From the results shown in Fig. 9 and Table 12, it can be underlined that optimal cutting parameters found to be cutting speed (Vc) of 180m/min, feed rate (f) of 0.08mm/rev, cutting depth (ap) of 0.15mm. The optimized surface roughness $Ra = 0.23\mu\text{m}$. Also, the optimized cutting force components are: [feed force (Fa) is decreased to 29.87N with a reduction of 6.88%, thrust force (Fr) is decreased to 116.87N with a reduction of 3.65%, tangential force (Ft) is decreased to 34.83N with a reduction of 19.05%.

Table12

Response optimization for surface roughness and cutting force components.

Vc (m/min)	f (mm/rev)	ap (mm)	Cutting forces			
			Surface roughness $Ra, \mu\text{m}$	Fa, N	Fr, N	Ft, N
180	0.08	0.15	0.23	29.87	116.5	34.83
Desirability			0.99	1		
Composite desirability = 0.99						

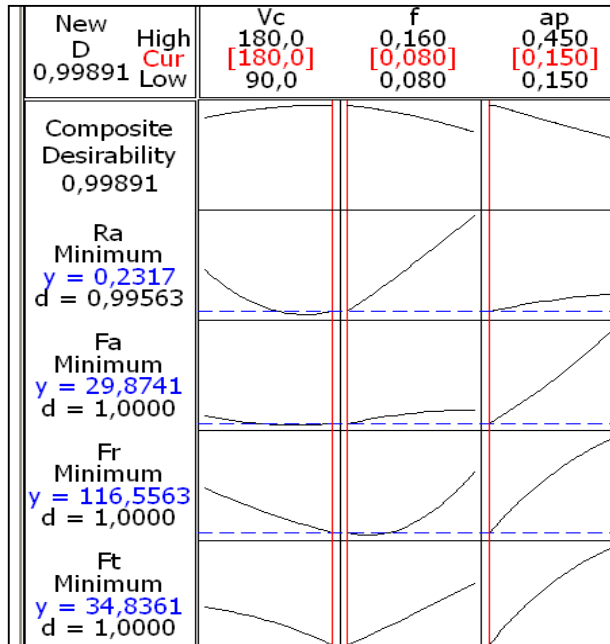


Fig.9. Response optimization for surface roughness and cutting force components

5. Conclusions

This paper proposes the RSM approach to predicted and optimized surface roughness and cutting forces based on cutting parameters (cutting speed, feed rate and depth of cut). The important findings are summarized as follows:

- 1) In general, the higher is the work material hardness, the higher is the machining forces. The thrust force presents higher values followed by the tangential and feed force.
- 2) The machining force components increase almost linearly as the feed rate and depth of cut are elevated.
- 3) Feed rate and depth of cut have the greatest influence on surface roughness and cutting forces, respectively.
- 4) Based on the analysis of the variance (ANOVA) results, the highly effective parameters on both the surface roughness and cutting forces were determined. Namely, the feed rate parameter is the main factor that has the highest importance on the surface roughness and accounts for 77.92% contribution in the total variability of the model. The cutting speed has a secondary contribution of 15.47%, whereas the depth of cut affects fairly the surface roughness. The feed force, thrust force and cutting force are affected strongly by the depth of cut and account for 90.22%, 67.64%, 69.44% contribution in the total variability of model, respectively.
- 5) An improvement in surface quality and lower cutting forces are observed at higher cutting speed with lower feed rate and depth of cut.
- 6) Prediction accuracy of surface roughness and cutting forces by RSM developed models is efficient both for the training and testing data set.
- 7) The developed model has high square values of the regression coefficients which indicated high association with variances in the predictor values.
- 8) Comparison of experimental and predicted values of the surface roughness and cutting forces show that a good agreement has been achieved between them.
- 9) Response optimization show that the optimal combination of cutting parameters are found to be cutting speed of 180m/min, feed rate of 0.08mm/rev, cutting depth of 0.15mm. For machining AISI 4140 steel in the hard turning process, the optimal values of the surface roughness (R_a) = 0.23 μ m and cutting force components (feed, thrust and cutting forces) represent a reduction of (6.88%, 3.65% and 19.05%), respectively. These values were compared to results of initial cutting parameters. In this study, the optimization methodology proposed is a powerful approach and can offer to scientific researchers as well industrial metalworking a helpful optimization procedure for various combinations of the workpiece and the cut material tool.

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