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Experimental investigation of cutting parameters influence on surface roughness and cutting forces in hard turning of X38CrMoV5-1 with CBN tool

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Abstract. This experimental investigation was conducted to determine the effects of cutting conditions on surface roughness and cutting forces in hard turning of X38CrMoV5-1. This steel was hardened at 50 HRC and machined with CBN tool. This is employed for the manufacture of helicopter rotor blades and forging dies. Combined effects of three cutting parameters, namely cutting speed, feed rate and depth of cut, on the six performance outputs-surface roughness parameters and cutting force components, are explored by analysis of variance (ANOVA). Optimal cutting conditions for each performance level are established. The relationship between the variables and the technological parameters is determined through the response surface methodology (RSM), using a quadratic regression model. Results show how much surface roughness is mainly influenced by feed rate and cutting speed. The depth of cut exhibits maximum influence on cutting force components as compared to the feed rate and cutting speed.

Keywords. Hard turning; RSM; CBN; ANOVA; cutting force; surface roughness.

1. Introduction

Hard turning is a process, in which materials in their hardened state (45–70 HRC) are machined with the single point cutting tools. This has become possible with the availability of the new cutting tool materials (cubic boron nitride and ceramics). Since a large number of operations are required to produce the finished product, if some of the operations can be combined, or eliminated, or can be substituted by the new process, product cycle time can be reduced and productivity can be improved. The traditional method of machining hardened materials includes

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rough turning, heat treatment, and then grinding process. Hard turning eliminates the series of operations required to produce the component and thereby reducing the cycle time and hence resulting in productivity improvement (Bouacha *et al* 2010; Tamizharasan *et al* 2006).

Cutting forces are the background for the evaluation of the necessary power machining (choice of the electric motor). They are also used for dimensioning of machine tool components and the tool body. They influence the deformation of workpiece machined, its dimensional accuracy, chip formation and machining system stability (Fnides *et al* 2008).

Surface roughness plays an important role as it influences the fatigue strength, wear rate, coefficient of friction, and corrosion resistance of the machined components. In actual practice, there are many factors which affect the surface roughness, i.e., tool variables, workpiece hardness and cutting conditions. Tool variables include tool material, nose radius, rake angle, cutting edge geometry, tool vibration, tool point angle, etc. Theoretical surface roughness achievable based on tool geometry and feed rate is given approximately by the formula: $Ra = 0.032\ f^2/r_\varepsilon$. In hard turning, surface finish has been found to be influenced by a number of factors such as feed rate, cutting speed, tool nose radius and tool geometry, cutting time, workpiece hardness, stability of the machine tool and the workpiece set up, etc. (Chen 2008; Sahin & Motorcu 2005). Huang *et al* (2006) presented a thorough review that discusses CBN tool material microstructure, encountered wear patterns and tool wear rate modelling under hard turning. Lima *et al* (2005) investigated the machinability of hardened steels at different levels of hardness and using a range of cutting tool materials. More specifically, the machinability of hardened AISI 4340 high strength low alloy steel and AISI D2 cold work tool steel. The results indicated that when turning AISI 4340 steel the surface roughness of the machined parts was improved as cutting speed was elevated and deteriorated with feed rate. Depth of cut presented little effect on the surface roughness values. Dilbag & Venkateswara (2007) have conducted the study on the influence of rake angle, cutting speed, feed rate and nose radius are primary influencing factors which effect the surface finish, the results indicated that the feed rate is a dominant factor affecting the surface roughness. Sahin & Motorcu (2005) showed that the feed rate was main influencing factor on the surface roughness. It increased with increasing the feed rate but decreased with increasing the cutting speed and the depth of cut, respectively. Bouacha *et al* (2010) investigated the effect of cutting speed, feed rate and depth of cut on surface roughness and cutting forces using three level factorial design (3^3) during machining of bearing steel (AISI 52100) with CBN tool. Results show how much surface roughness is mainly influenced by feed rate and cutting speed and that the depth of cut exhibits maximum influence on the cutting forces as compared to feed rate and cutting speed.

Thiele & Melkote (1999) investigated the effect of cutting edge geometry on surface roughness in finish hard turning by cutting bars (28.6 mm diameter) of AISI 52100 steel at three different hardness values (41; 47; 57 HRC). They used low-CBN inserts with four edge radius. The experiments were carried out using different feed rates (0.05, 0.10, 0.15 mm/rev) and fixed cutting speeds (121.9 m/min) and depth of cut (0.254 mm). The authors observed that the effect of the cutting edge hone on surface roughness decreases with increase in workpiece hardness. Also, they noted that the cutting edge geometry has a significant effect on the axial and radial cutting force components. Suresh *et al* (2002) studied a genetic algorithmic approach for optimizing the surface finish prediction model for cutting carbon steel. This approach gives minimum and maximum values of surface roughness and their respective optimal machining conditions. Horng *et al* (2008) developed a model for the prediction of surface roughness followed by an optimization model for the determination of optimal cutting conditions in machining austenitic Hadfield steel. The quadratic model of RSM associated with the sequential approximation optimization (SAO) method was used to find optimum values of machining parameters. Drawish (2000) studied the effect of the tools and cutting parameters on surface roughness of 718 nickel alloy. This work also showed that feed rate has the dominant effect on surface roughness amongst the parameters studied, irrespective of tool materials used. Yallese *et al* (2009) found that a cutting speed of 120 m/min is an optimal value for machining 100Cr6 (60 HRC) using CBN7020. In addition, the feed rate effect on roughness is satisfactorily predicted by a power model deduced from experimental data. A correlation between surface roughness and tool wear is proposed for the usual cutting speed ranges. In an original work carried out by Çaydaş (2009), the effects of the cutting speed, feed rate, depth of cut, workpiece hardness, and cutting tool type on surface roughness, tool flank wear, and maximum tool–chip interface temperature during an orthogonal hard turning of hardened/tempered AISI 4340 steels were investigated. Dureja *et al* (2009) investigated the effect of cutting speed, depth of cut, workpiece hardness and feed rate on surface roughness and flank wear using a three-level factorial design, during machining of AISI H11 with a coated-mixed ceramic tool. The study indicated that feed rate and workpiece hardness are the most significant factors affecting the surface roughness. Singh & Kumar (2006) 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. The authors used Taguchi's parameter design approach and concluded that the effect of depth of cut and feed in variation of feed force were affected more as compare to speed. Kirby *et al* (2004) developed the prediction model for surface roughness in turning operation. The regression model was developed by a single cutting parameter and vibrations along three axes were chosen for in-process surface roughness prediction system.

By using multiple regression and Analysis of Variance (ANOVA) a strong linear relationship among the parameters (feed rate and vibration measured in three axes) and the response (surface roughness) was found. The authors demonstrated that spindle speed and depth of cut might not necessarily have to be fixed for an effective surface roughness prediction model. Özel *et al* (2007) studied for prediction of surface roughness and tool flank wear by utilizing the neural network model in comparison with regression model. The data set from measured surface roughness and tool flank wear were employed to train the neural network models. Predictive neural network models were found to be capable of better predictions for surface roughness and tool flank wear within the range in between they were trained. Aouici *et al* (2010) studied on machining of slide-lathing grade X38CrMoV5-1 steel treated at 50 HRC by a CBN 7020 tool to reveal the influences of cutting parameters: feed rate, cutting speed and depth of cut on cutting forces as well as on surface roughness. The authors found that tangential cutting force was very sensitive to the variation of cutting depth. It was observed that surface roughness was very sensitive to the variation of feed rate and that flank wear had a great influence on the evolution of cutting force components and on the criteria of surface roughness.

Our study aims to develop models, using the RSM approach, for predicting surface roughness parameters and cutting force components during machining of X38CrMoV5-1 steel with CBN7020. The RSM as employed in this investigation the relation-ship between various process parameters and the response factors within the desired limits. It is an efficient tool for designing the experiments and, by applying ANOVA and regression analysis, the response factors can be modelled in terms of input parameters. The developed model describes the interaction (single/two parameters) of various input parameters with respect to response factors. RSM has been proven to be a very powerful tool for solving optimization problems in manufacturing environments. The quadratic models of RSM with desirability function optimization have been used in this study to arrive at the optimal setting of machining parameters.

Table 1. Chemical composition of X38CrMoV5-1steel.

Composition	(Wt %)
C	0.35
Cr	5.26
Mo	1.19
V	0.50
Si	1.01
Mn	0.32
S	0.002
P	0.016
Other components	1.042
Fe	90.31

2. Experimental procedures

2.1 *Material, workpiece and tool*

Turning experiments were performed in dry conditions using lathe type SN 40C with 6.6 KW spindle power. The workpiece material was X38CrMoV5-1, hot work steel which is popularly used in hot form pressing. Its resistance to high temperature and its aptitude for polishing enable it to answer the most server requests in hot dieing and moulds under pressure. Its chemical composition is given in table 1.

The workpiece is 80 mm in diameter and it is hardened to 50 HRC. Cutting insert is removable and offered eight squared working edges. The chosen CBN tool in commercially known as CBN7020 and it is essentially made of 57% CBN and 35% Ti(C, N). Its standard designation is SNGA120408 S01020 and is manufactured by Sandvik. The physical properties of the CBN7020 tool are summarized in table 2.

Tool holder is codified as PSBNR 25 × 25 K12 with a common active part tool geometry described by $\chi_r = +75°$, $\lambda = -6°$, $\gamma = -6°$ and $\alpha = +6°$. For three components measurement of cutting forces in X, Y and Z directions were recorded using a standard quartz dynamometer (Kistler 9257B) allowing measurements from −5 to 5 KN. Instantaneous roughness criteria measurement (Ra, Rt and Rz) for each cutting condition were obtained from a Surftest 201 Mitutoyo roughness meter coupled with a radius and moves linearly on the working surface. The length examined is 5.0 mm with a basic span of 0.8 mm. The measured values of Ra are within the range 0.05 to 40 μm while for Rt and Rz, they lay between 0.3 and 160 μm. Roughness measurements were directly obtained on the same without disassembling the turned part in order to reduce uncertainties due to resumption operations. The measurements were repeated 3 times out of 3 generatrices equally positioned at 120° and the result is an average of these values for a given machining pass.

Table 2. Physical properties of CBN7020 tool.

Material	Hardness HV (daN/mm^2)	Tenacity ($MPa\ m^{1/2}$)	Young's modulus (GPa)	Density (g/cm^3)	Grain size (μm)
CBN7020	2800	4.2	570	4.3	2.5

Table 3. Assignment of the levels to the factors.

Level	Cutting speed Vc (m/min)	Feed rate f (mm/rev)	Depth of cut ap (mm)
1	120	0.08	0.15
2	180	0.12	0.30
3	240	0.16	0.45

2.2 *Experiments design*

The response surface methodology (RSM) is the 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 (Chiang 2008). These are, in the order, (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.

In the current study, the relationship between the cutting conditions and the technology parameters aspect is given as:

$$Y = \phi(Vc, f, ap), \tag{1}$$

where Y is the desired machinability aspect and ϕ is the response function. The approximation of Y is proposed by using a nonlinear (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

$$Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i,j}^{k} b_{ij} X_i X_j + \sum_{i=1}^{k} b_{ii} X_i^2, \tag{2}$$

where b_0 is the free term of the regression equation, the coefficients, $b_1, b_2, \ldots b_k$ and $b_{11}, b_{22}, \ldots b_{kk}$ are the linear and the quadratic terms respectively; while $b_{12}, b_{13}, \ldots b_{k-1}$ are the interacting terms. The experimental plan is developed to assess the influence of cutting speed (V_c), feed rate (f) and depth of cut (ap) on the surface roughness parameters (Ra, Rt and Rz) and cutting force components (Fa, Fr and Fv). Three levels are defined for each cutting variable as given in table 3. The variable levels are chosen within the intervals recommended by cutting tool manufacturer. Three cutting variables at three levels led to a total of 27 tests.

3. Results and discussion

The plan of tests was developed with the aim of relating the influence of cutting speed (Vc), feed rate (f) and depth of cut (ap), with the surface roughness parameters and cutting force components.

Table 4 shows all values of surface roughness and cutting forces. The surface roughness was obtained in the range of 0.22–0.80, 2.00–5.60 and 0.50–3.40 μm for Ra, Rt and Rz, respectively. The feed force (Fa), thrust force (Fr) and cutting force (Fv) were obtained in range of 20.49–150.64 N, 43.28–396.67 N and 38.5–393.70 N, respectively. Furthermore, thrust force is about ∼1.12 higher than cutting force. König *et al* (1984) reported that thrust force is about twice that

Table 4. Experimental results for surface roughness parameters and cutting force components.

Test	Factors			Cutting force components			Surface roughness parameters		
number	ap, mm	f, mm/rev	Vc, m/min	Fa, N	Fr, N	Fv, N	Ra, μm	Rt, μm	Rz, μm
1	0.45	0.16	180	143.62	329.03	305	0.59	4.2	2.28
2	0.15	0.16	180	54.10	111.89	87.86	0.58	4.2	2.1
3	0.45	0.16	120	143.03	396.67	393.70	0.76	5.1	3.4
4	0.30	0.12	240	57.44	113.83	89.78	0.42	3.2	1.33
5	0.30	0.12	180	64.54	111.46	87.42	0.48	3.5	1.73
6	0.30	0.08	120	70.09	195.07	171.03	0.41	3.1	1.80
7	0.30	0.08	240	50.56	122.17	98.13	0.24	2.1	0.60
8	0.15	0.16	240	48.62	74.56	50.53	0.48	3.6	1.57
9	0.15	0.12	240	26.26	43.28	38.5	0.39	3.0	1.27
10	0.15	0.08	180	31.54	102.29	78.26	0.27	2.3	0.50
11	0.30	0.12	120	72.52	211.19	188.55	0.68	4.8	2.43
12	0.30	0.16	120	104.43	262.63	238.59	0.79	5.4	3.0
13	0.45	0.12	180	87.82	232.60	208.57	0.46	3.3	1.80
14	0.45	0.12	240	112.06	210.01	185.95	0.42	3.1	1.40
15	0.15	0.16	120	82.44	164.88	140.85	0.80	5.6	3.03
16	0.45	0.08	180	82.58	224.15	200.12	0.28	2.2	1.07
17	0.45	0.08	120	85.44	291.44	267.41	0.38	3.2	2.0
18	0.30	0.16	180	109.21	180.74	156.7	0.59	4.2	2.16
19	0.15	0.08	240	20.49	89.98	65.95	0.22	2.0	0.60
20	0.15	0.08	120	50.39	121.45	97.42	0.40	3.0	1.70
21	0.45	0.16	240	150.64	339.77	315.74	0.49	3.5	1.70
22	0.15	0.12	180	35.72	60.12	40.26	0.44	3.4	1.63
23	0.30	0.08	180	56.38	104.51	80.47	0.28	2.4	0.86
24	0.30	0.16	240	86.94	134.09	110.04	0.51	3.7	1.60
25	0.15	0.12	120	52.81	147.68	123.65	0.66	5.0	2.50
26	0.45	0.12	120	110.71	313.73	289.7	0.69	4.6	2.80
27	0.45	0.08	240	105.1	186.71	162.68	0.24	2.0	0.73

of cutting force in hard turning. The thrust force is larger than cutting force in hard turning is also reported by Fnides *et al* (2008).

3.1 *Graphic analysis*

Figure 1 expresses the evolution of surface roughness criteria versus cutting speed, for several feed rates. According to the graph, it can be seen that the surface roughness increase with increase feed rates, because its increase generates helicoid furrows the result tool shape helicoid movement tool-workpiece. These furrows are deeper and broader as the feed rate increases (Fnides *et al* 2008). For this reason, weak feed rate have to be employed during turning operation. Similar results were reported by Bouacha *et al* (2010) when turning AISI 52100 steel (64 HRC) using CBN tool. The interactions $(Vc \times ap)$, $(ap \times H)$, $(f \times f)$ and the cutting speed (Vc) do not show a significant contribution on the surface roughness evolution. The best surface roughness was achieved at the lowest feed rate and highest cutting speed.

In figure 2 the evolution of cutting forces with the cutting speed for different feed rate can be seen. From figure 2, it can be realized that the cutting forces decrease with increase cutting speed. This figure shows that lower cutting speed and the higher feed rate resulted in higher

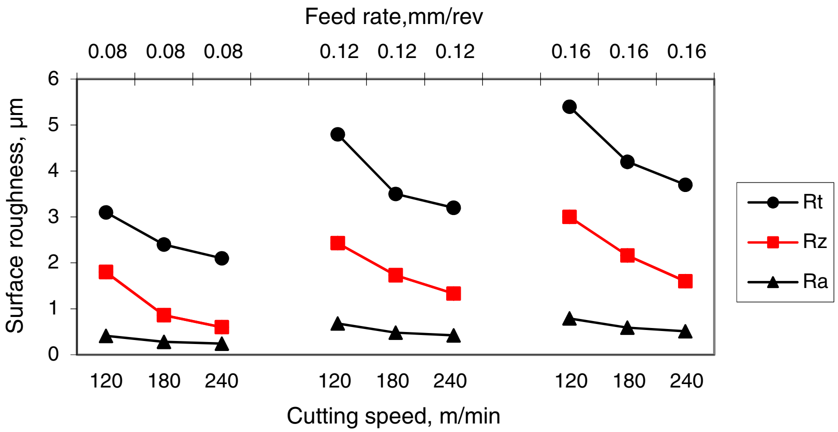

Figure 1. Effect of cutting speed on surface roughness at various feed rates.

cutting forces. Similar results were obtained by Lalwani *et al* (2008) when turning MDN250 steel (50 HRC) using coated ceramic tool.

3.2 *ANOVA and effects of factors*

The ANOVA of the data with the surface roughness parameters and cutting force components, with the objective of analysing the influence of cutting speed (Vc), feed rate (f) and depth of cut (ap) on the total variance of the results were carried out.

The table of ANOVA shows the degrees of freedom (DF), sum of squares (SC), mean squares (MS), F-values (F) and probability (P) in addition to the percentage contribution (Cont. %) of each factor and different interactions. A low P-value (≤ 0.05) indicates statistical significance for the source on the corresponding response (i.e., $\alpha = 0.05$, or 95% confidence level), this indicates that the obtained models are considered to be statistically significant, which is desirable; as it demonstrates that the terms in the model have a significant effect on the response.

The other important coefficient, R^2, which is called coefficient of determination in the resulting ANOVA tables, is defined as the ratio of the explained variation to the total variation and is a

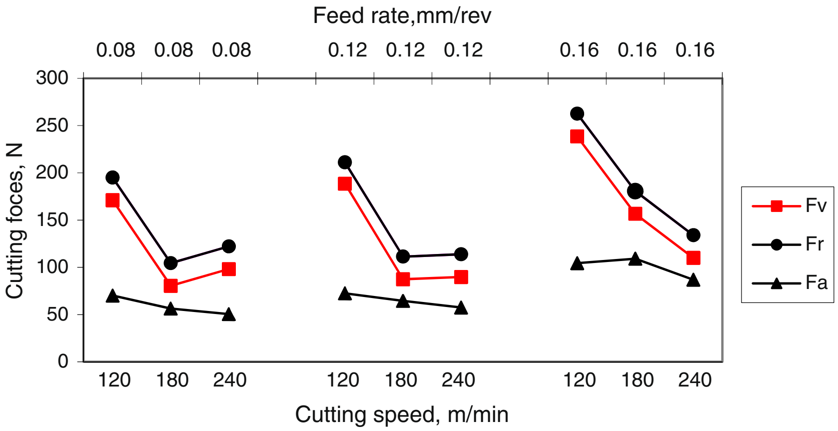

Figure 2. Effect of cutting speed on cutting forces at various feed rates.

Table 5. Analysis of variance (ANOVA) for Ra.

Term.	DF	SC	MS	F	P	Cont.%	Remarks
ap	1	0.00027222	0.00027222	0.8228515	0.3770	0.04	Not significant
f	1	0.45760556	0.45760556	1383.21337	< 0.0001	59.11	Significant
Vc	1	0.2592	0.2592	783.488969	< 0.0001	33.48	Significant
$ap \times f$	1	7.5E-05	7.5E-05	0.22670398	0.6400	0.01	Not significant
$ap \times Vc$	1	0.000675	0.000675	2.04033586	0.1713	0.09	Not significant
$Vc \times f$	1	0.01203333	0.01203333	36.3733948	< 0.0001	1.55	Significant
$ap \times ap$	1	0.00115741	0.00115741	3.49851827	0.0787	0.15	Not significant
$f \times f$	1	0.01742407	0.01742407	52.6680935	< 0.0001	2.25	Significant
$Vc \times Vc$	1	0.02002963	0.02002963	60.5439579	< 0.0001	2.59	Significant
Error	17	0.00562407	0.00033083			0.73	
Total	26	0.7740963					

measure of the fit degree. When R^2 approaches to unity, it indicates a good correlation between the experimental and the predicted values.

3.2a *ANAOVA for surface roughness*: The characterization of the machined surface quality was limited to the criteria of total roughness (Rt), arithmetic mean roughness (Ra) and mean depth of roughness (Rz).

Arithmetic mean roughness (Ra): Table 5 shows that the main effects of the cutting speed, feed rate and the products cutting speed/cutting speed, feed rate/feed rate and cutting speed/feed rate are significant with respect to arithmetic mean roughness (Ra), the depth of cut factor and the interaction depth of cut/depth of cut, cutting speed/depth of cut, feed rate/depth of cut do not present a statistical significance on the arithmetic mean roughness (Ra). However, a qualitative comparison can be made. For example, (Feng 2001) found that the depth of cut does not impact on the surface roughness of turned surfaces. However, feed rate, nose radius, work material and speeds, the tool point angle have a significant impact on the observed surface roughness using the fractional factorial experimentation approach (El Baradie 1997). Ra model is given by equation (3). Its coefficient of correlation R^2 is 98.13%.

Table 6. Analysis of variance for Rt.

Term.	DF	SC	MS	F	P	Cont.%	Remarks
ap	1	0.045	0.045	2.34382979	0.1442	0.15	Not significant
f	1	16.4355556	16.4355556	856.04766	< 0.0001	56.58	Significant
Vc	1	10.2755556	10.2755556	535.203404	< 0.0001	35.38	Significant
$ap \times f$	1	0.04083333	0.04083333	2.12680851	0.1630	0.14	Not significant
$ap \times Vc$	1	0.04083333	0.04083333	2.12680851	0.1630	0.14	Not significant
$Vc \times f$	1	0.3675	0.3675	19.1412766	0.0004	1.27	Significant
$ap \times ap$	1	0.04166667	0.04166667	2.17021277	0.1590	0.14	Not significant
$f \times f$	1	0.66666667	0.66666667	34.7234043	< 0.0001	2.30	Significant
$Vc \times Vc$	1	0.80666667	0.80666667	42.0153191	< 0.0001	2.78	Significant
Error	17	0.32638889	0.01919935			1.12	
Total	26	29.0466667					

Table 7. Analysis of variance for Rz.

Term.	DF	SC	MS	F	P	Cont.%	Remarks
ap	1	0.2888	0.2888	27.9857073	< 0.0001	1.83	Significant
f	1	6.6978	6.6978	649.039717	< 0.0001	42.41	Significant
Vc	1	7.81442222	7.81442222	757.244227	< 0.0001	49.48	Significant
$ap \times f$	1	0.00853333	0.00853333	0.82690917	0.3759	0.054	Not significant
$ap \times Vc$	1	0.02803333	0.02803333	2.71652583	0.1177	0.177	Not significant
$Vc \times f$	1	0.081675	0.081675	7.91458671	0.0120	0.517	Significant
$ap \times ap$	1	0.02080741	0.02080741	2.01630891	0.1737	0.132	Not significant
$f \times f$	1	0.17567407	0.17567407	17.0234183	0.0007	1.112	Significant
$Vc \times Vc$	1	0.50074074	0.50074074	48.5234896	< 0.0001	3.171	Significant
Error	17	0.17543241	0.01031955			1.112	
Total	26	15.7919185					

Total roughness (Rt): From the analysis of table 6, it can be seen that the feed rate factor (Cont.≈ 56.58%) and cutting speed (Cont.≈ 35.38%) have statistical significance on the total roughness (Rt). The depth of cut and interactions depth of cut/depth of cut, feed rate/depth of cut do not present a statistical significance on the total roughness (Rt). Rt model is given by equation (4). Its coefficient of correlation R^2 is 97%.

Mean depth of roughness (Rz): Finality, from table 7, it can be realized that the cutting speed factor (Cont. ≈ 49.48%) and the feed rate factor (Cont. ≈ 42.41%) are noticed. The depth of cut and interaction feed rate/depth of cut do not present a statistical significance on the mean depth of roughness (Rz). Rz model is given by equation (5) and its coefficient of correlation R^2 is 97.22%.

3.2b *ANOVA for cutting force*: The ANOVA of the data with cutting force components, with an objective of analysing the influences of cutting speed, of feed and depth of cut on the total variance of results.

Feed force (Fa): From table 8, we can observe that the depth of cut (Cont. ≈ 63.67%) and feed rate (Cont. ≈ 22.83%) have great influence on the feed force (Fa) obtained, especially the depth

Table 8. Analysis of variance for Fa.

Term.	DF	SC	MS	F	P	Cont.%	Remarks
ap	1	21261.2821	21261.2821	504.184441	<0.0001	63.67	Significant
f	1	7624.47842	7624.47842	180.804873	<0.0001	22.83	Significant
Vc	1	718.836806	718.836806	17.0463066	0.0007	2.15	Significant
$ap \times f$	1	552.570408	552.570408	13.1035091	0.0021	1.65	Significant
$ap \times Vc$	1	1177.90268	1177.90268	27.9324737	<0.0001	3.53	Significant
$Vc \times f$	1	16.1704083	16.1704083	0.3834608	0.5440	0.05	Not significant
$ap \times ap$	1	116.01338	116.01338	2.75111072	0.1155	0.35	Not significant
$f \times f$	1	1030.00936	1030.00936	24.4253707	0.0001	3.08	Significant
$Vc \times Vc$	1	181.316713	181.316713	4.29969676	0.0536	0.54	Significant
Error	17	716.884071	42.1696513			2.15	
Total	26	33395.4643				100	

Table 9. Analysis of variance for Fr.

Term.	DF	SC	MS	F	P	Cont.%	Remarks
ap	1	143114.283	143114.283	438.261478	<0.0001	63.53	Significant
f	1	17021.355	17021.3550	52.1248057	<0.0001	7.55	Significant
Vc	1	34441.7509	34441.7509	105.471602	<0.0001	15.29	Significant
$ap \times f$	1	8672.02568	8672.02568	26.5565023	<0.0001	3.85	Significant
$ap \times Vc$	1	109.143008	109.143008	0.33423062	0.5708	0.048	Not significant
$Vc \times f$	1	338.034675	338.034675	1.03516975	0.3232	0.15	Not significant
$ap \times ap$	1	5930.21282	5930.21282	18.1601988	0.0005	2.63	Significant
$f \times f$	1	5425.2294	5425.2294	16.6137789	0.0008	2.40	Significant
$Vc \times Vc$	1	4677.71682	4677.71682	14.3246575	0.0015	2.08	Significant
Error	17	5551.34991	326.549995			2.47	
Total	26	225281.102				100	

of cut factor. The interactions feed rate/feed rate (Cont. ≈ 3.08%), cutting speed/depth of cut (Cont. ≈ 3.53%) and feed rate/depth of cut (Cont. ≈ 1.65%) present significant parameters.Fa model is given by equation (6). Its coefficient of correlation R^2 is 95.16%.

Thrust force (Fr): From table 9, it can be apparently shown that the most significant factor on the thrust force is depth of cut, which explains 63.53% contribution of total variation. The next largest contribution is cutting speed with the contribution of 15.29. The interactions cutting speed/cutting speed (Cont. ≈ 2.08%), feed rate/feed rate (Cont. ≈ 2.41%) depth of cut/depth of cut (Cont. ≈ 2.63%) and feed rate/depth of cut (Cont. ≈ 3.85%) present percentages of significance of contribution on the specific thrust force (Fr). This indicates that feed rate has little influence on thrust force and it agrees with the results of Özel *et al* (2005). Fr model is given by equation (7). Its coefficient of correlation R^2 is 92.22%.

Tangential force (Fv): Equally, from table 10 we can be observe the depth of cut factor (Cont. ≈ 62.06%), the cutting speed factor (Cont. ≈ 15.22%) and feed rate factor (Cont. ≈ 8.08%). The interactions cutting speed/cutting speed (Cont. ≈ 2.35%), feed rate/feed rate (Cont. ≈ 2.15%), depth of cut/depth of cut (Cont. ≈ 3.01%), and feed rate/depth of cut (Cont. ≈ 4.4%) have great influence on the cutting force (Fv), especially the depth of cut. The

Table 10. Analysis of variance for Fv.

Term.	DF	SC	MS	F	P	Cont.%	Remarks
ap	1	143748.071	143748.071	482.240158	<0.0001	62.06	Significant
f	1	18721.770	18721.770	62.8070295	<0.0001	8.08	Significant
Vc	1	35251.320	35251.320	118.25969	<0.0001	15.22	Significant
$ap \times f$	1	10184.430	10184.430	34.1663121	<0.0001	4.40	Significant
$ap \times Vc$	1	566.775	566.775	1.90139388	0.1858	0.24	Not significant
$Vc \times f$	1	685.540	685.540	2.29982439	0.1478	0.30	Not significant
$ap \times ap$	1	6974.586	6974.586	23.3980591	0.0002	3.01	Significant
$f \times f$	1	4982.209	4982.209	16.7141132	0.0008	2.15	Significant
$Vc \times Vc$	1	5437.063	5437.06338	18.2400382	0.0005	2.35	Significant
Error	17	5067.427	298.083991			2.19	
Total	26	231619.195				100	

interactions cutting speed/feed rate and cutting speed/depth of cut do not present percentages of significance of contribution on the tangential force obtained. Fv model is given by equation (6). Its coefficient of correlation R^2 is 86.40%. Fv model is given by equation (8). Its coefficient of correlation R^2 is 93.26%.

It should be noticed that the error associated with the ANOVA tables has 0.73, 1.12 and 1.112% for surface roughness parameters Ra, Rt and Rz, respectively, 2.15, 2.47 and 2.19% for cutting force components Fa, Fr and Fv %, respectively.

3.3 *Regression equations*

The relationship between the factors and the performance measures were modelled by quadratic regression. The regression equations obtained were as follows:

$$\begin{aligned} Ra = {} & 0.08463 + 0.963ap + 14.56f - 6.44 \times 10^{-3} Vc \\ & - 0.41667ap \times f + 8.33 \times 10^{-3} ap \times Vc \\ & - 0.01319f \times Vc - 0.617ap^2 - 33.68f^2 + 1.6049 \times 10^{-4} Vc^2 \end{aligned} \tag{3}$$

$$\begin{aligned} Rt = {} & 1.46944 + 1.888ap + 89.93f - 0.04255 \times 10^{-3} Vc - 9.722ap \\ & \times f + 6.481 \times 10^{-3} ap \times Vc \\ & - 0.0729f \times Vc - 3.703ap^2 - 208.33f^2 + 1.0185 \times 10^{-4} Vc^2 \end{aligned} \tag{4}$$

$$\begin{aligned} Rz = {} & 1.6412 + 0.77ap + 48.43f - 0.03413Vc - 4.44ap \\ & \times f - 5.37 \times 10^{-3} ap \times Vc \\ & - 0.00343f \times Vc - 2.617ap^2 - 106.94f^2 + 8.024 \times 10^{-5} Vc^2 \end{aligned} \tag{5}$$

$$\begin{aligned} Fa = {} & 222.45 - 222ap - 1703.03f - 0.93Vc + 1130.97ap \times f - 1.1ap \times Vc \\ & - 0.48368f \times Vc + 195.43ap^2 + 8188.88f^2 + 1.52 \times 10^{-3} Vc^2 \end{aligned} \tag{6}$$

$$\begin{aligned} Fr = {} & 724.61 - 721.24ap - 4687.78f - 3.155Vc + 4480.41ap \\ & \times f - 0.335ap \times Vc \\ & - 2.211f \times Vc + 1397.25ap^2 + 18793.75f^2 + 7.75 \times 10^{-3} Vc^2 \end{aligned} \tag{7}$$

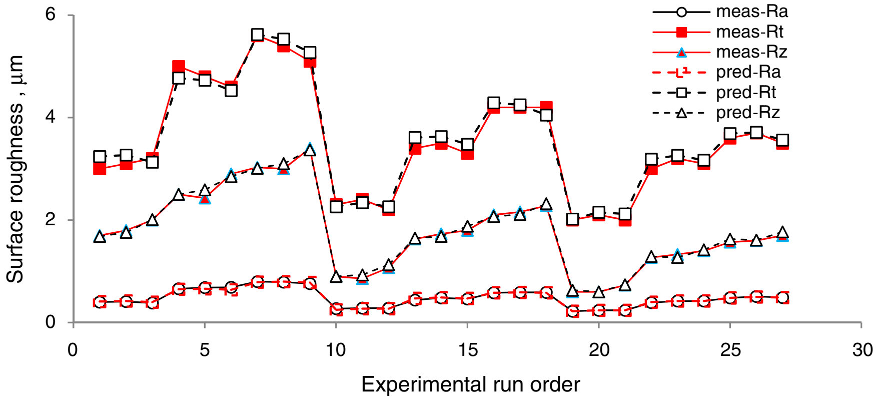

Figure 3. Comparison between measured and predicted values for surface roughness.

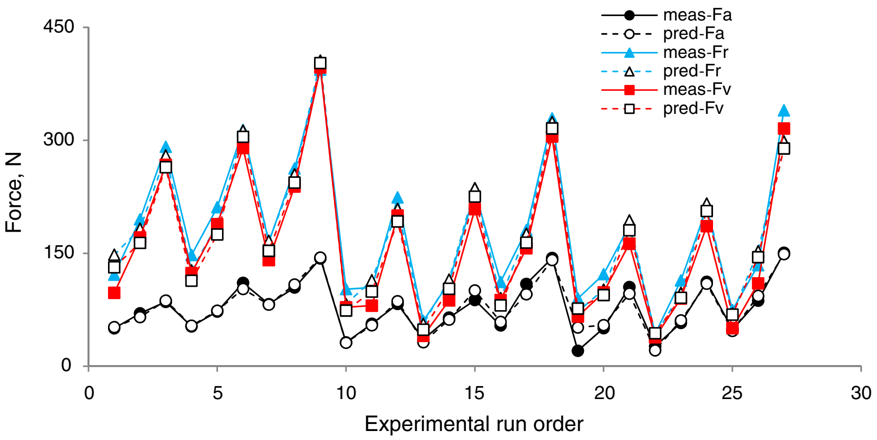

Figure 4. Comparison between measured and predicted values for cutting forces.

$$
\begin{aligned}
Fv = {} & 685.81 - 758.62ap - 4405.9f - 3.14Vc + 4855.41ap \times f - 0.7631ap \times Vc \\
& - 3.149f \times Vc + 1515.3ap^2 + 18010.06f^2 + 8.36 \times 10^{-3}Vc^2 \qquad (8)
\end{aligned}
$$

These equations give the expected value of surface roughness parameters and cutting force components for any combination of factor levels given that the levels are within the ranges given in table 4. The above mathematical model can be used to predict the values of the surface roughness parameters and cutting force components the limits of the factors studied. The differences between the measured and predicted response are illustrated in figures 3 and 4. The results of comparison were proven to predict the values of surface roughness parameters and cutting force components close to those readings recorded experimentally with a 95% confidence interval. Good agreement is observed between these values as seen in figures 5 and 6.

3.4 *Responses surface analysis*

Figure 7a presents the influence of cutting speed (Vc), feed rate (f) and depth of cut (ap) on arithmetic mean roughness (Ra), The effects of the cutting speed (Vc), feed rate (f) and depth of cut (ap) on total roughness (Rt) are shown in figure 7b. The estimated surface response (mean

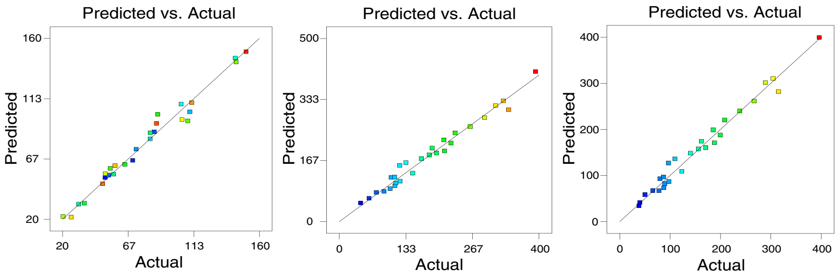

Figure 5. Comparison of measured and predicted value for (Fa, Fr and Fv).

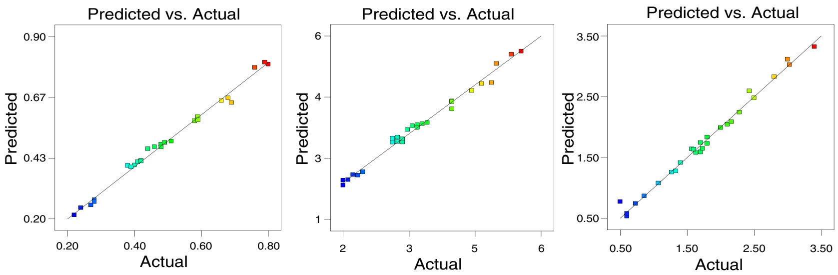

Figure 6. Comparison of measured and predicted value for (Ra, Rt and Rz).

depth of roughness, Rz) in relation to the cutting speed (Vc), feed rate (f) and depth of cut (ap) are shown in figure 7c.

The estimated cutting force components, namely, the feed force, thrust force and cutting force in relation to cutting conditions are given in figures 8a to c. As seen from these figures, the cutting forces components increase with the increase in depth of cut and decrease with the increase cutting speed.

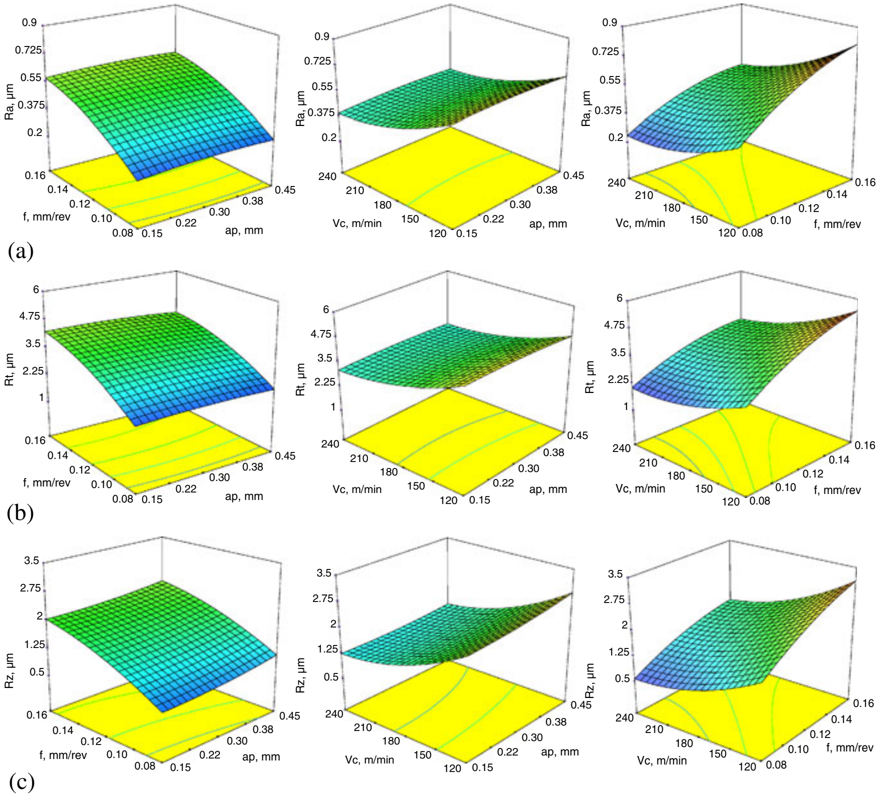

Figure 7. Estimated responses surface of surface roughness parameters versus Vc, f and ap.

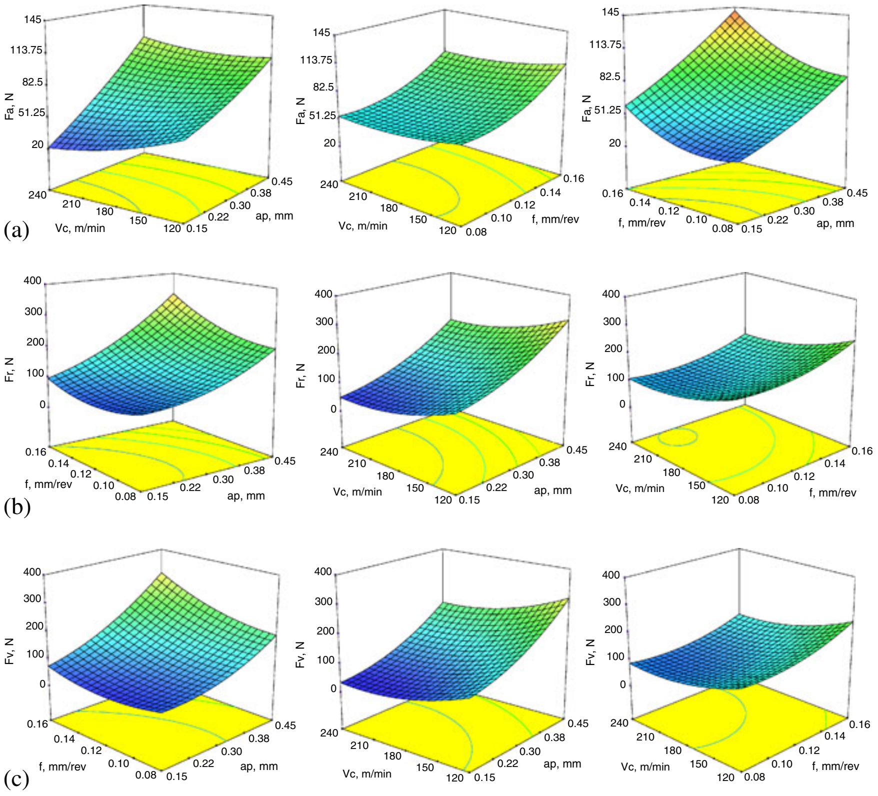

Figure 8. Estimated responses surface of cutting force components versus Vc, f and ap.

4. Optimization of cutting conditions

The optimal manufacturing conditions for machining hot work steel (X38CrMoV5-1) with the constraints of cutting parametric range is to find the optimal value of cutting parameters in order to minimize the values of the surface roughness parameters (Ra, Rt and Rz) and cutting force components (Fa, Fr and Fv) during the hard turning process. The constraints used during the

Table 11. Constraints for optimization of cutting conditions.

Condition	Goal	Lower limit	Upper limit
Cutting speed, Vc	Is in range	120	240
Feed rate, f	Is in range	0.08	0.16
Depth of cut, ap	Is in range	0.15	0.45
Ra (μm)	Minimize	0.22	0.8
Rt (μm)	Minimize	2	5.6
Rz (μm)	Minimize	0.5	3.4
Fa (N)	Minimize	20.49	150.64
Fr (N)	Minimize	43.28	393.7
Fv (N)	Minimize	38.5	396.67

Table 12. Response optimization for surface parameters and cutting force components.

Parameters	Goal	Optimum combination Vc, m/min	f, mm/rev	ap, mm	Lower	Target	Upper	Predicted response	Desirability
Ra (µm)	Minimum	227.48	0.08	0.15	0.22	0.22	0.8	0.219	1
Rt (µm)	Minimum	227.48	0.08	0.15	2	2	5.6	1.965	1
Rz (µm)	Minimum	227.48	0.08	0.15	0.5	0.50	3.4	0.558	1
Fa (N)	Minimum	227.48	0.08	0.15	20.49	20.49	150.64	22.76	0.997
Fr (N)	Minimum	227.48	0.08	0.15	43.28	43.28	393.70	77.08	0.975
Fv (N)	Minimum	227.48	0.08	0.15	38.50	38.50	396.67	60.32	0.985

optimization process are summarized in table 11. The optimal solutions are reported in table 12 in order of decreasing desirability level.

Table 12 shows the RSM optimization results for the surface roughness parameters and cutting force components. The optimum cutting parameters obtained in table 8 are found to be cutting speed of 227.48 m/min, feed rate of 0.08 mm/rev and depth of cut 0.15 mm. The optimized surface roughness parameters are $Ra = 0.219$ µm, $Rt = 1.965$ µm and $Rz = 0.558$ µm. In addition, the optimized cutting force components are $Fa = 22.76$ N, $Fr = 77.08$ N and $Fv = 60.32$ N.

5. Conclusion

In this study, a detailed experimental investigation is presented for the effects of cutting speed, feed rate and depth of cut on the cutting force components and the surface roughness parameters in hard turning of X38CrMoV5-1 (50 HRC) steel with CBN tool. A three-factor, three-level factor technique can be employed easily to develop a mathematical model for predicting surface roughness parameters and cutting force components of cutting conditions during the turning operation.

The results have indicated that the effect of depth of cut on the cutting force components is remarkably significant. According to presented results, the surface roughness is highly affected by feed rate, whereas the cutting speed has negative effect and depth of cut a negligible influence.

The optimum machining conditions combinations for minimizing surface roughness parameters and cutting force components for hard turning of the X38CrMoV5-1within the ranges of variable studied are also tested through confirmation experiments that show fairly good agreement with prediction of empirical models developed. However, the validity of the procedure is limited to the range of factors considered for the experimentation.

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Nomenclature

ap	Depth of cut, mm.
f	Feed rate, mm/rev.
Fa	Feed force, N.
Fr	Thurst force, N.
Fv	Tangential force, N.
H	Workpiece hardness.
HRC	Rockwell hardness.
Ra	Surface roughness, μm.
Rt	Total roughness, μm.
Rz	Mean depth of roughness, μm.
Vc	Cutting speed, m/min.
α	Clearance angle, degree.
γ	Rake angle, degree.
λ	Inclination angle, degree.
χ	Major cutting edge angle, degree.

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