Surface Roughness, Machining Force and Flank Wear in Turning of Hardened AISI 4340 Steel with Coated Carbide Insert: Cutting Parameters Effects

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Abstract

The current experimental study is to investigate the effects of process parameters (cutting speed, feed rate and depth of cut) on performance characteristics (surface roughness, machining force and flank wear) in hard turning of AISI 4340 steel with multilayer CVD (TiN/TiCN/Al2O3) coated carbide insert. Combined effects of cutting parameter (v, f, d) on performance outputs (Ra, Fm and VB) are explored employing the analysis of variance (ANOVA). An L9 Taguchi standard design of experiments procedure was used to develop the regression models for machining responses, within the range of parameters selected. Results show that, feed rate has statistical significance on surface roughness and the machining force is influenced principally by the feed rate and depth of cut whereas , cutting speed is the most significant factor for flank wear followed by cutting speed. The desirability function approach has been used for multi-response optimization. Based on the surface roughness, machining force and flank wear, optimized machining conditions were observed in the region 147 m/min cutting speed and 0.10 mm/rev feed rate and 0.6 mm depth of cut.

***Keywords**: Hard turning, AISI 4340 steel, Surface roughness, Machining force, Flank wear, ANOVA*

1. Introduction

The demand for a better performance and a more economical manufacturing process is combined today to improve the product quality, reduce cost and at the same time to comply with the environmental aspects in order to remain competitive. In recent years, hard turning of steel parts have become very popular and effective technology replacing cylindrical grinding operations that are often hardened above 45 HRC. Hard turning process enables manufacturers to increase product quality and its efficiency, while decreasing the cost and processing time. This process offers many potential benefits compared to grinding such as [1,2]: higher productivity, reduced setup times and energy consumption, process flexibility, surface finish closer to grinding, less environmental problems without the use of cutting fluid. During hard turning, complex and mutual interactions are created between tool and work piece at the contact surface. Consequently, significant forces and high temperature are recorded causing wear and sometimes breakage of the tool [3]. As a result of which the precision of the finished work piece dimension as well as the surface roughness are altered. Therefore, the knowledge of surface finish, machining force and tool wear in hard turning process under given cutting factors is of great importance, being a dominating criteria of material machinability, to both the design, manufacture of machine tools, as well as to user. In this regard, surface roughness, machining (cutting) force and tool wear produced during hard turning has been analyzed by many researchers.

Suresh et al. [4] investigated cutting force and surface roughness while machining hardened steel using multi-layer TiN/TiCN/Al2O3 coated carbide inserts. They observed minimum cutting force and surface roughness at low feed, low depth of cut and high cutting speed. Bouacha et al. [5] investigated surface roughness (Ra) and cutting force (Fc) values created in hard turning of AISI 52100 bearing steel (64 HRC) with CBN cutting tool. Machining tests are conducted as per Taguchi L27 orthogonal array with different cutting conditions. Cutting parameters which are the most effective on Ra are the feed rate and cutting speed while depth of cut is the parameter that greatly affects Fc value. Lalwani et al. [6] applied chamfered and honed edges to identify the effect of cutting parameters on cutting forces and surface roughness. They found that cutting speed has no significant effect on forces and surface roughness; however, the feed rate provides primary contribution and most significantly influences the latter. Ozel et al. [7] 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 work piece hardness, cutting edge geometry, feed rate and cutting speed on surface roughness are statistically significant. Horng et al. [8] developed RSM model using CCD in the hard turning using uncoated Al2O3/TiC mixed ceramics tool for flank wear and surface roughness. Flank wear was influenced principally by the cutting speed and the interaction effect of feed rate with nose radius of tool. The cutting speed and the tool corner radius affected surface roughness significantly. Aouici et al. [9] have applied response surface methodology (RSM) to optimize the effect of cutting parameters at the different levels of workpiece hardness on surface roughness and cutting force components in hard turning of AISI H11 with CBN tool. Results showed that the cutting force components were influenced principally by depth of cut and workpiece hardness; however, both feed rate and workpiece hardness had statistical significance on surface roughness. In the similar way, Dureja et al. [10] applied RSM to investigate the effect of cutting parameters on flank wear and surface roughness in hard turning of AISI H11 steel with a coated-mixed ceramic tool. The study indicated that the flank wear is influenced principally by feed rate, depth of cut and workpiece hardness whereas, feed rate and workpiece hardness are the most significant factors affecting the surface roughness. Aslan et al. [11] employed the Taguchi technique and ANOVA to optimize cutting parameters (v,f.d) for surface roughness and flank wear when turning hardened AISI 4140 steel (63 HRC) with mixed ceramic (Al2O3+TiC) tool. Davim and Figueira [12] employed orthogonal array and ANOVA to investigate the machinability such as flank wear, specific cutting force and surface roughness in hard turning of cold work tool steel with ceramic tools. They concluded that with an appropriate choice of cutting parameters it is possible to obtain a surface roughness with Ra < 0.8 µm that allows cylindrical grinding operation to be eliminated. Bartarya and Choudhury [13] studied the effect of cutting parameters on cutting force and surface roughness during finish hard turning AISI52100 grade steel. In this study, experiment was design by a full factorial design for developing the force and surface roughness regression models, within the range of parameters selected. More et al. [14] experimentally investigated the effects of cutting speed and feed rate on tool wear, surface roughness and cutting forces in turning of AISI 4340 hardened steel using CBN–TiN-coated carbide inserts. In addition, cost analysis based on total machining cost per part was also performed for the economic comparison of CBN–TiN-coated and PCBN inserts. Sharma et al. [15] studied machining variables such as cutting forces and surface roughness which are measured during turning at different cutting parameters such as approaching angle, speed, feed and depth of cut. The data obtained by experimentation is analyzed and used to construct model using neural networks. In an original work carried out by Çaydas [16], 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. Sahoo and Sahoo [17] investigated flank wear, surface roughness, chip morphology and cutting forces in hard turning of AISI 4340 steel (47 HRC); using uncoated and multilayer TiN and ZrCN coated carbide inserts. Experimental results showed that multilayer TiN/TiCN/Al2O3/TiN coated carbide inserts performed better than the uncoated and TiN/TiCN/Al2O3/ZrCN coated carbide inserts.

In the present study, an attempt has been made to investigate the effect of cutting parameters (cutting speed, feed rate and depth of cut) on the performance characteristics (surface roughness, machining force and flank wear) in finish hard turning of AISI 4340 bearing steel hardened at 49 HRC with multilayer CVD TiN/TiCN/Al2O3 coated carbide inserts. An L9 Taguchi standard orthogonal array (OA) is adopted as the experimental design. The combined effects of the cutting parameters on performance characteristics are investigated while employing the analysis of variance (ANOVA). The relationship between cutting parameters and performance characteristics through the multiple linear regression analysis are developed.

2. Experimental Setup and Procedure

In this study, bars of AISI4340 steel (100 mm diameter and 400 mm long) were used as work material. This material is known for properties like high tensile strength, shock resistance, good ductility and wear resistance, which finds application in heavy vehicle crank shafts, connecting rods, gear shafts, cam shafts, spindles, etc. The chemical composition of the workpiece material (AISI 4340) was checked by Spectro metal analyzer (Spectromax) and is given in Table 1. Initially, the bars were heat treated at 900°C (austenization temperature) for 30 minutes and quenched in oil. After that, tempering was carried out for 1 hr at 4200C followed by air cooling. The hardness after heat treatment was obtained as 49 HRC.

The cutting tool used was multilayer CVD coated (TiN/TiCN/Al2O3) carbide inserts in accordance with ISO designation of CNMG 120408. The inserts were clamped onto a tool holder with a designation of PCLNL2525M12 (ISO). Combination of the insert and the tool holder resulted in negative rake angle γ = −60, clearance angle = 50, approach angle = 950 and including angle = 800. Machining experiment has been performed on a high rigid CNC lathe (JOBBER XL, AMS, India) equipped with variable spindle speed from 50 to 3500 rpm and 16KW maximum spindle power with Sinumeric controller under dry environment. A hole was drilled on the face of the workpiece to allow is to be supported at the tailstock and cleaned by removing a 0.5 mm depth of cut from the outside surface of the workpiece, prior to the actual machining. Surface roughness tester (SJ-301, Mitotoyo make) was used to measure surface roughness (Ra) after each turning operation. During the turning tests, cutting forces (Fc, Ff and Fr) in three directions were recorded using a piezoelectric tool post dynamometer (Kistler 9257B), which is coupled with the charge amplifier. The measured three force components are represented with a machining force (Fm), which are evaluated by the formula: Fm = $\sqrt{(Fc^2 + F_f{}^2 + Fr^2)}$. The flank wear formed on cutting inserts was measured by Mitutoyo TM-500 tool makers' microscope with 40x magnification. The experimental setup is shown in Fig. 1.

The working ranges of the parameters for subsequent design of experiment, based on Taguchi's L9 orthogonal array (OA) design have been selected. In the present experimental study, cutting speed (v), feed (f) and depth of cut (d) have been considered as cutting parameters. The identified parameters and their associated levels are given in Table 2. According to Taguchi quality design concept, for three levels and three parameters, nine experiments are to be performed and hence L9 orthogonal array was selected as shown in Table 3.

Table 1 Chemical composition of AISI 4340 steel (wt %)

C	Si	Mn	P	S	Cr	Mo	Ni	Fe
0.384	0.231	0.613	0.025	0.028	1.007	0.230	1.418	Balance

Table 2 Cutting parameters and their levels

Parameters	Symbol	Unit	Levels		
			1	2	3
Cutting speed	v	m/min	140	200	260
Feed	f	mm/rev	0.1	0.2	0.3
Depth of cut	d	mm	0.6	0.8	1.0

Table 3 Orthogonal Array L9 of Taguchi Experiment Design and Experimental Results

Run	v	f	d	Ra (μm)	Fm (N)	VB (mm)
1	140	0.1	0.6	0.53	438	0.042
2	140	0.2	0.8	1.55	632	0.076
3	140	0.3	1.0	2.63	1119	0.116
4	200	0.1	0.8	0.55	423	0.088
5	200	0.2	1.0	1.16	751	0.129
6	200	0.3	0.6	1.85	601	0.165
7	260	0.1	1.0	0.52	480	0.188
8	260	0.2	0.6	0.77	455	0.184
9	260	0.3	0.8	1.67	694	0.300

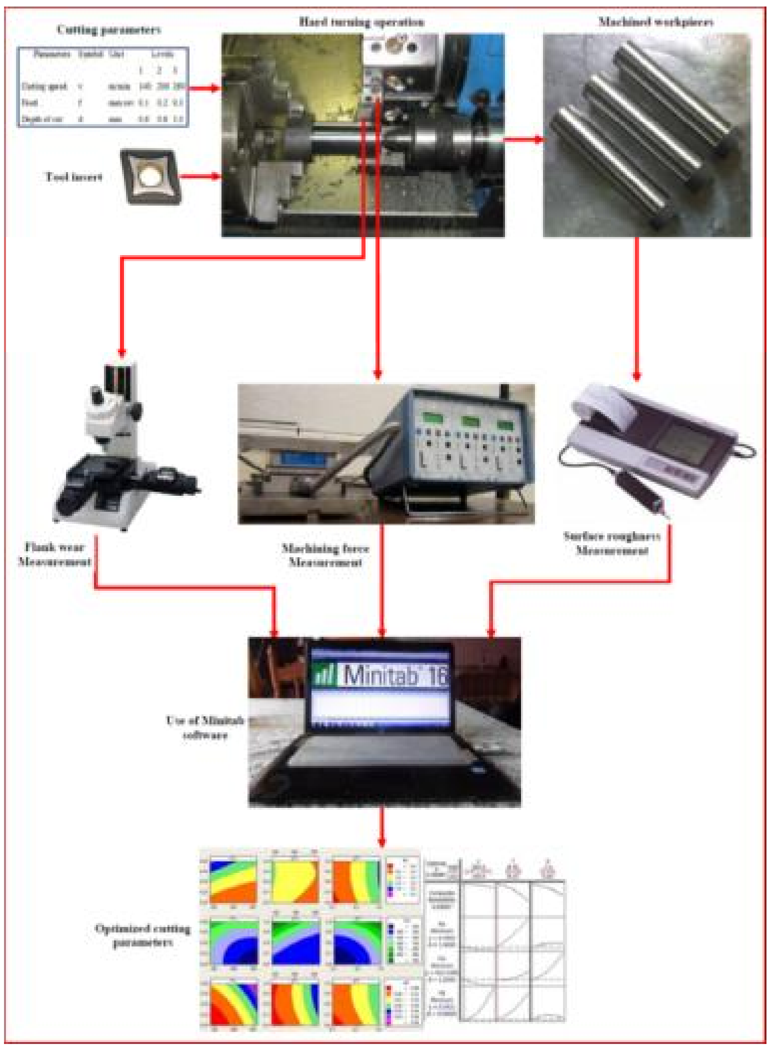

Fig1. Experimental setup

3. Results and Discussion

3.1 Surface Roughness (Ra)

In order to quantify the influence of process (cutting) parameters on the selected machining characteristics (surface roughness, machining force and flank wear), analysis of variance (ANOVA) was performed. The table of ANOVA shows the degree of freedom (DF), sum of squares (SS), mean squares (MS), F-values (F) and probability (P) in addition to the percentage contribution (%C) of each factor. A low P-value (≤ 0.1) indicates statistical significance for source on the corresponding response (i.e. $\alpha = 0.1$ or 90% confidence level) [18].

From Table 4(a) it can be seen that feed was found to be only significant factor on surface roughness (Ra) with 80.85% contribution as its P-value is less than 0.1. The next largest contribution comes from cutting speed with 12.23%, followed by depth of cut 5.21%, which does not have statistical significance. This indicates depth of cut has little influence on surface roughness (Ra).

Figure 1 shows the effect of various cutting parameters on surface roughness (Ra). It is evident that as feed increases surface roughness (Ra) also increases. That was expected, it is well known that the theoretical geometrical surface roughness is primarily a function of the feed for a given nose radius and changes with the square of the feed rate value [19]. Surface roughness decreases with increasing cutting speed. This can be explained by the decreased built-up-edge (BUE) formation, due to higher temperature generated in the tool-chip contact area as a function of increased cutting speed. When BUE is large and unstable, surface roughness increases. Similar results can be found in the literature [20].

Table 4 Analysis of variance for surface roughness, machining force and flank wear

Source	DF	Seq SS	Adj SS	Adj MS	F	P value	C (%)
(a) Analysis of variance for surface roughness (Ra)							
v	2	0.52722	0.52722	0.26361	7.16	0.123	12.23
f	2	3.48509	3.48509	1.74256	47.34	0.021	80.85
d	2	0.22462	0.22462	0.11231	3.05	0.247	5.21
Error	2	0.07362	0.07362	0.03681			1.71
Total	8	4.31056					100
S = 0.191862 R-Sq = 98.29% R-Sq(adj) = 93.17%							
(b) Analysis of variance for machining force (Fm)							
v	2	56257	56257	28128	4.13	0.195	14.39
f	2	192235	192235	96117	14.12	0.066	49.18
d	2	128774	128774	64387	9.46	0.096	32.95
Error	2	13617	13617	6808			3.48
Total	8	390882					100
S = 82.5133 R-Sq = 96.52% R-Sq(adj) = 86.07%							
(c) Analysis of variance for flank wear (VB)							
v	2	0.0330942	0.0330942	0.0165471	28.82	0.034	69.7
f	2	0.0123416	0.0123416	0.0061708	10.75	0.085	26.0
d	2	0.0008949	0.0008949	0.0004474	0.78	0.562	1.9
Error	2	0.0011482	0.0011482	0.0005741			2.4
Total	8	0.0474789					100
S = 0.0239606 R-Sq = 97.58% R-Sq(adj) = 90.33%							

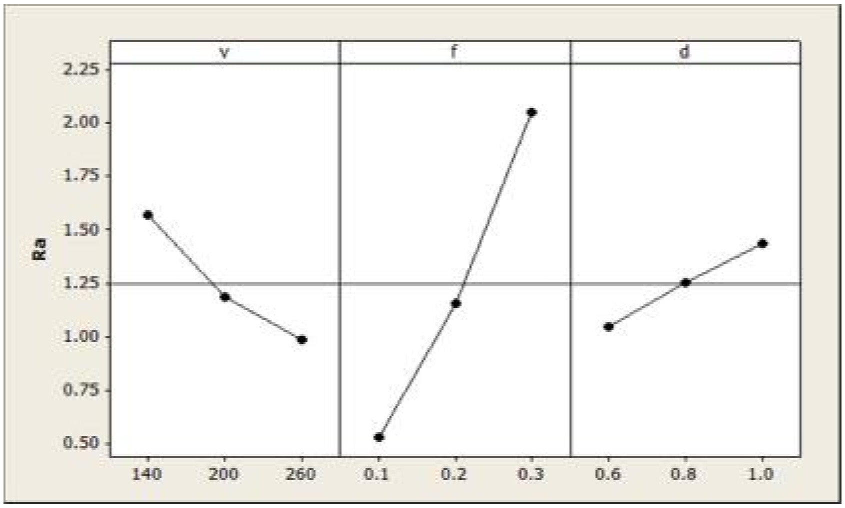

Fig2. Main effect plots for surface roughness (Ra)

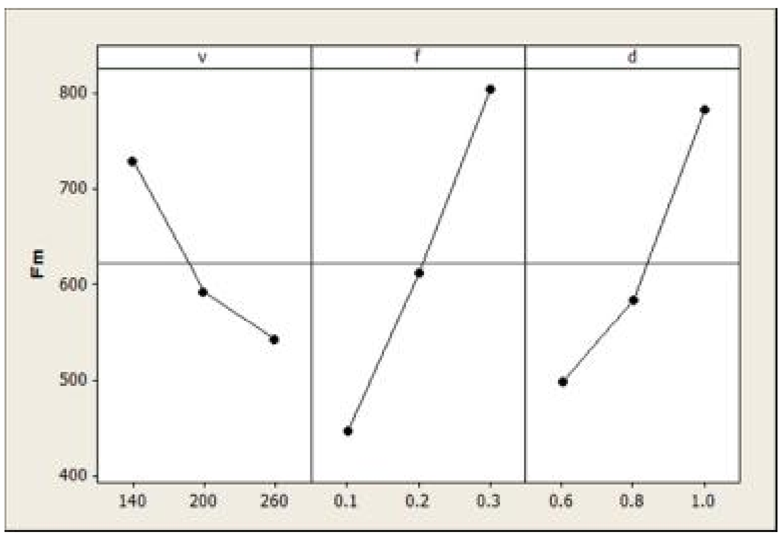

Fig3. Main effect plots for machining force (Fm)

3.2 Machining Force (Fm)

Table 4(b) shows that feed rate and depth of cut are significant terms on machining force (Fm). The feed rate has maximum influence on the machining force (Fm) with the contribution 49.18%, followed by depth of cut (32.95%) and cutting speed (14.39%).

Figure 3 shows the main effect plots for machining force (Fm). The graph indicates that with the increase of feed and depth of cut, the machining force also increases. As the depth of cut and feed rate increases, tool-chip interface area increase which leads to increase in machining force. On the other hand, cutting speed has decreasing control on machining force (Fm) decrease. This machining force decrease is explained by the plastic softening of machined material under the effect of the increase in the cutting temperature [21].

3.3 Flank Wear (VB)

From analysis of variance (ANOVA) for flank wear (Table 4(c)), it is revealed that cutting speed has been observed to be the most significant variable affecting flank wear (VB) followed by feed rate as its F value is greater than F table value and P-value is less than 0.1 at 90% confidence level. As a result of the assessment of tool flank wear, the percentage contributions of factors cutting speed, feed, and depth of cut were found to be: 69.7%, 26% and 1.9% respectively.

In Fig. 4 the main effects for flank wear (VB) are plotted. It indicates that the flank wear increases with an increase in cutting speed. The rate of flank wear is considerably lower with an increase in the feed rate than with the cutting speed. According to Horng et al. [8], the increase in the flank wear rate with increased cutting speed could be due to the frictional heat generation in contact between the tool wedge and the machined work surface is more than heat generation due to an increase in the feed rate.

3.4Regression Equations

The relationship between the factors and the performance measures were modeled by multiple linear regressions. The regression equations obtained were as follows.

Ra = - 0.070 - 0.00486 v + 7.58 f + 0.967 d (R2 = 97.1) (1)

Fm = 4 - 1.56 v + 1788 f + 713 d (R2 = 93.7) (2)

VB = - 0.216 + 0.00122 v + 0.438 f + 0.0350 d (R2 = 92.2) (3)

The Anderson–Darling test and normal probability plots of the residuals versus the predicted response for the surface roughness, machining force and flank wear are plotted in Fig. 5. The data closely follows the straight line. The null hypothesis is that the data distribution law is normal and the alternative hypothesis is that it is non-normal. Using the P-value which is greater than alpha of 0.1 (level of significance), the null hypothesis cannot be rejected (i.e., the data follow a normal distribution). It implies that the models proposed are adequate.

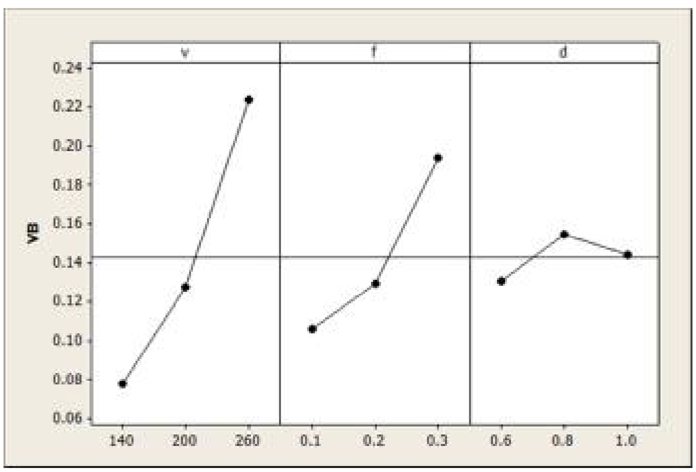

Fig4. Main effect plots for flank wear (VB)

Table 5 Response Optimization for Surface Roughness, Machining Force and Flank Wear

Parameters	Goal	Optimum combination v	f	d	Lower	Target	Upper	Predicted response	Desirability
Ra	Minimum	147	0.1	0.6	0.52	0.52	2. 63	0.498	1
Fm	Minimum	147	0.1	0.6	423	423	1119	421.4	1
VB	Minimum	147	0.1	0.6	0.042	0.042	0.300	0.042	0.99962
Composite desirability = 0.99987									

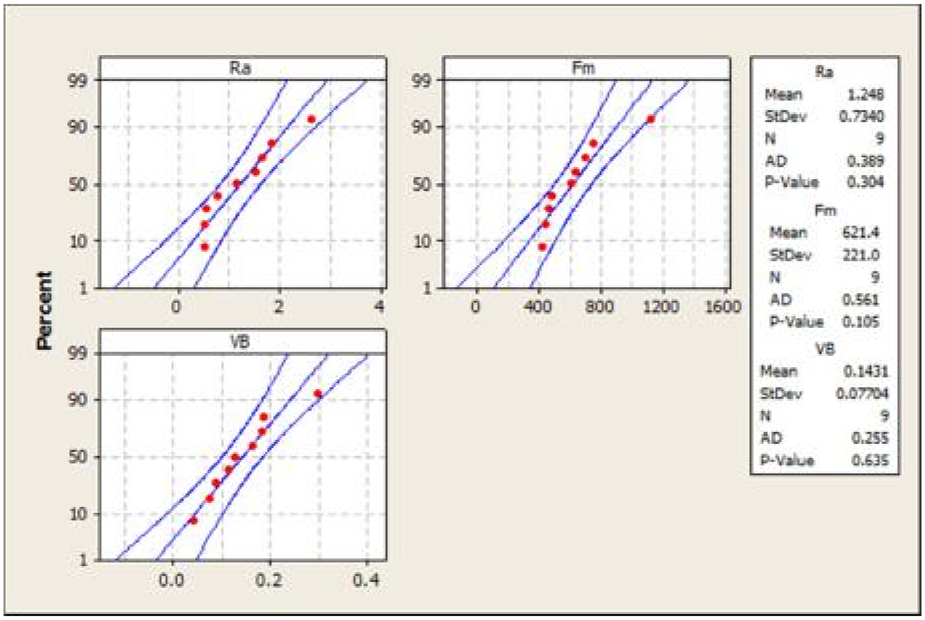

Fig5. Normal probability plots of surface roughness, machining force and flank wear

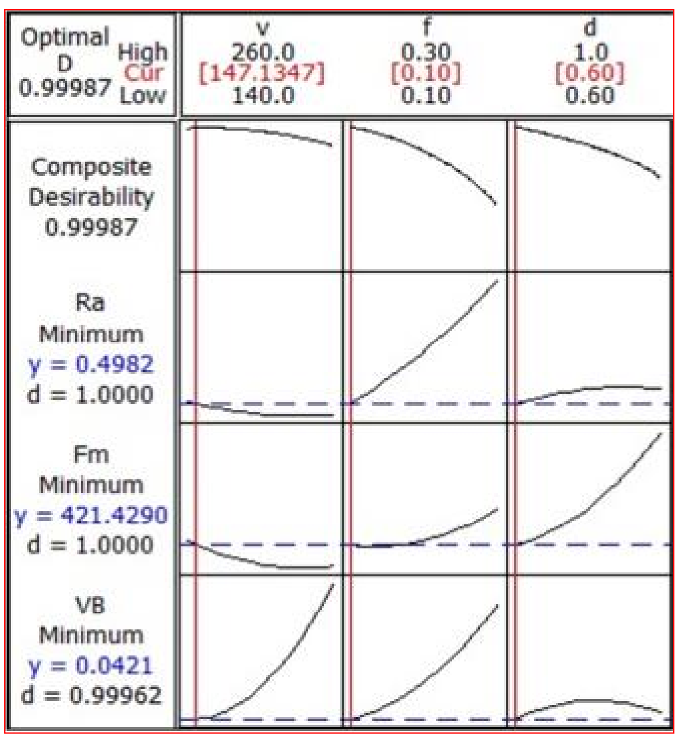

Fig6. Response optimization plot for surface roughness (Ra), machining force (Fm) and flank wear (VB)

3.5 Optimization of Response

One of the most important aims of experimental study is to find optimal cutting parameters in order to obtain the desired machined surface roughness, the lowest machining force and minimum tool wear during hard turning process. To end this, the response surface optimization is an ideal technique for determination of the cutting parameters in turning operation. Table 5 shows the RSM optimization results for the surface roughness, machining force and flank wear. The optimum cutting parameters obtained in Fig. 6 are found to be cutting speed of 147 m/min, feed rate 0.10 mm/rev and depth of cut 0.6 mm. The optimized surface roughness, machining force and flank wear are 0.98 µm, 421.43 N and 0.042 mm.

Conclusions

In this study, it has been shown that factorial design of experiments combined with techniques of regression may be applied for modelling the behavior of functions depending on several variables. This has been carried out in an efficient way and without being necessary to perform a large number of experiments.

The ANOVA illustrates that among the cutting parameters; feed rate has the greater influence on surface roughness (80.85%), followed by cutting speed (12.23%) and depth of cut (5.21%). Higher feed rates lead to higher roughness values, whereas cutting speed has a contrary effect.

Also the higher the feed rate and depth of cut, the higher the machining force, whereas the higher cutting speed, the lower the machining force. The feed rate exhibits maximum influence on machining force as compared to depth of cut and cutting speed.

The cutting speed is the cutting condition that has the highest physical as well statistical influence on the tool flank wear (69.71%) right after the feed rate (26%), whilst the depth of cut has a less effect (1.9%). Increases of cutting speed and feed rate affect the tool flank wear positively.

Simultaneous optimization of the machining characteristic (surface roughness, machining force and flank wear) when hard turning of AISI 4340 steel with multilayer CVD coated (TiN/TiCN/Al2O3) carbide insert was achieved with a cutting speed v=147 m/min, feed rate f=0.10 mm/rev and depth of cut d=0.6 mm.

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