Modeling of surface roughness in dry hard turning of X38CrMoV5-1 machined by coated carbide GC3015 using Taguchi technique

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Abstract. In the present work, the performance of multilayer coated carbide tool was investigated considering the effect of cutting parameters during turning of hardened X38CrMoV5-1 high alloy steel (~50 HRC). This steel is free from tungsten on Cr-Mo-V basis. It is employed for the manufacture of plastic moulds subject to high stress, helicopter rotor blades and forging dies. Nine experimental runs based on an orthogonal array (L_9) of the Taguchi method were performed to derive objective functions to be optimized within the experimental domain. The objective functions were selected in relation to the parameters of the cutting process: surface roughness criteria. The correlations between the cutting parameters and performance measures, like surface roughness, were established by multiple linear regression models. Highly significant parameters were determined by performing an Analysis of variance (ANOVA). Arithmetic mean roughness (*Ra*), total roughness (*Rt*) and mean depth of roughness (*Rz*) get affected mostly by feed rate. Its contributions on *Ra, Rt* and *Rz* are (71.72, 22.16 and 48.46%), respectively.

Keywords: Taguchi technique; X38CrMoV5-1; coated carbide tool; surface roughness; RSM.

Nomenclature

ap Depth of cut, mm

f Feed rate, mm/rev

HRC Rockwell hardness

R^2 Coefficient of determination

Ra Arithmetic mean roughness, μm

Rt Total roughness, μm

Rz Mean depth of roughness, μm

r_ε Tool nose radius, mm

Vc Cutting speed, m/min

α Relief angle, degree

γ Rake angle, degree

λ Inclination angle, degree

χ Major cutting edge angle, degree

1. Introduction

At present, hard machining of steel is a topic of immense interest for industrial production and scientific research since it offers a number of potential advantages, including lower equipment costs, shorter setup time, high accuracy, fewer process steps, greater part geometry flexibility, and usually there is no need to use cutting fluid during turning of hardened steel.

Taguchi's orthogonal arrays are highly fractional designs, used to estimate main effects using very few experimental runs. These designs are not only applicable for two level factorial experiments, but also can investigate main effects when factors have more than two levels. Designs are also available to investigate main effects for some mixed level experiments where the factors included do not have the same number of levels. For example, a four-level full factorial design with five factors requires 1024 runs while the Taguchi orthogonal array reduces the required number of runs to 16 only [1-2].

A three-level full factorial design with three factors (3^3 = 27) requires 27 runs while the Taguchi orthogonal array reduces the required number of runs to 9 only (L_9 = 9) [3-4].

The machining of hardened steels using polycrystalline cubic boron nitride (PCBN) and ceramic tools is widely accepted as a best replacement to costly grinding operations. However, development in the cemented carbide grades, coating materials and coating deposition technologies have attracted many researchers in the field of hardened steel machining using coated carbide tools [5].

In dry hard turning of AISI H11 steel treated at 50 HRC machined by the following cutting materials: the carbides (H13A and GC3015), the reinforced ceramic CC670 and the cermets (CT5015 and GC1525) and for this cutting regime: V_c = 120 m/min, a_p = 0.15 mm and f = 0.08 mm/rev, the tool life of the uncoated cermets CT5015 and the coated cermets GC1525 are less than 2 minutes. The tool life of the uncoated carbide H13A is 4.5 minutes. The tool life of the reinforced ceramic CC670 is only 8 minutes. However the tool life of the coated carbide GC3015 is 16 minutes. This experimental study confirms that in dry hard turning of this steel and for the cutting regime tested, the coated carbide GC3015 is the most powerful tool in terms of wear resistance and lifespan [6].

The productivity in terms of volume chip carved of five cutting tools at two different cutting conditions in straight hard turning of X38CrMoV5-1 (50 HRC) was investigated. For the first cutting regime (V_c = 120 m/min, a_p = 0.15 mm et f = 0.08 mm/rev), the productivity of the coated cermets GC1525, the uncoated cermets CT5015, the uncoated carbide H13A, the reinforced ceramic CC670 and the coated carbide GC3015 are (1440; 2160; 6480; 11520 and 23040) mm^3, respectively. The productivity of these two selected tools, i.e. reinforced ceramic CC670 and coated carbide GC3015 for the second cutting regime (V_c = 90 m/min, a_p = 0.15 mm and f = 0.08 mm/rev) are (12960 and 30780) mm^3, respectively. These results prove that the coated carbide GC3015 is more efficient than other tools used in terms of productivity [7].

In the theoretical study of *Ra* for mild, Response Surface Methodology is used to investigate the relationship between laser machining parameter with responses. The cutting parameters studied here are cutting speed, frequency and duty cycle. The dimensions of *Ra* for mild steel are directly proportional to the duty cycle and frequency and inversely proportional to cutting speed can be observed with the help of model equation. For mild steel the best value for the surface roughness (6.37µm) can be obtained at high cutting speed (1200 mm/min) value and low duty cycle value (60%). It is clear that surface roughness decreases with increase in cutting speed. Surface roughness increases with increase in the duty cycle. Frequency is not a major factor in influencing the outcome of the surface roughness. The effect of cutting speed and duty cycle on the surface roughness is more as compared to frequency [8].

The statistical analysis based on ANOVA, during turning AISI 420 steel with coated carbide tool GC2015, has established that the feed rate has the highest influence on the surface roughness (81.69%). In the second rank come both of Vc^2 and f^2 with 6.071% and 6.071% contributions, respectively. The depth of cut parameter has a very less effect compared to that of the feed rate. The best surface finish is obtained at lower cutting speed with lower feed rate and lower depth of cut. The reduced model obtained for *Ra* using the RSM quadratic modeling, with correlation coefficient R^2 of 95.27%, showed strong correlation with the input data. The comparison between predicted and measured values for surface roughness proved that predicted values are very close to experimental ones. The model can be employed to predict the surface roughness patterns developed. Based on the response surface optimization and the composite desirability method of RSM, the optimal turning parameters are found to be as follows: *Vc* = 120 m/min, *f* = 0.08 mm/rev and *ap* = 0.15 mm. The optimized response is *Ra* = 0.523 µm with a composite desirability of 0.987. From the confirmation test, it can be seen that the empirical model developed is reasonably accurate. The error of surface roughness is *Ra* = maximum value 5.12% and minimum 0.84% [9].

In dry hard turning of X38CrMoV5-1 steel treated at 50 HRC machined by whisker ceramic tool (Al_2O_3+SiC), the results of ANOVA show that the feed rate is the dominant factor affecting surface finish. Its contribution on *Ra* is 85.70%, on *Rt* 96.57% and on *Rz* 98.95%. The second factor influencing *Ra*, *Rt* and *Rz* is cutting speed. Its contribution on *Ra* is 8.12%, on *Rt* 1.91% and on *Rz* 0.45%. As for the depth of cut, its contribution is not important. The interaction $Vc \times f$ is significant on *Rt* and *Rz* [10].

The aim of the present work is, thus, to model surface roughness in hard turning of X38CrMoV5-1. Nine machining tests were carried out under dry conditions with the multilayer coated carbide GC3015 inserts using Taguchi technique.

The model predicting equations for cutting force and surface roughness were developed. To calculate constants and coefficients of these models, the software's Minitab 15 and Design-Expert 8 characterized by analysis of variance (ANOVA), multiple linear regression and response surface methodology (RSM) were exploited.

In order to achieve this: statistical analysis of the experimental, the analysis of variance (ANOVA) was applied. This latter is a computational technique that enables the estimation of the relative contributions of each of the control factors to the overall measured response. In this work, the parameters were used to develop mathematical model using multiple linear regression and response surface methodology (RSM). RSM is a collection of mathematical and statistical techniques that are useful for the modelling and analysis of problems in which response of interest is influenced by several variables and the objective is to optimize the response [11-15].

2. Experimental procedure

Experiments were performed using commercially available coated tungsten based cemented carbide inserts. The grade of the inserts is GC3015 (CVD coating layer sequence TiCN/Al_2O_3/TiN) with three main layers and several more sub-layers of coating with a total thickness of 14 µm (figure 1). The main coating layers include: medium temperature titanium carbonitride (TiCN), fine grain alpha structure aluminum oxide (Al_2O_3), and a thin layer of titanium carbonitride (TiCN) and titanium nitride (TiN). The insets have identical geometry designated by ISO as SNMA 120408-KR [16].

A right hand style tool holder designated by ISO as PSBNR 2525M12, has a geometry of the active part characterized by the following angles: χ = 75°; α = 6°; γ = -6°; λ = -6°, was used for mounting the inserts.

The workpiece used for experiments was of 300 mm length and 75 mm in diameter, hardened to 50 HRC. Its grade is X38CrMoV5-1, hot work steel which is popularly used in hot form forging. It is employed for the manufacture of the module matrices of door for car and helicopter rotor blades. Its chemical composition is given in Table 1.

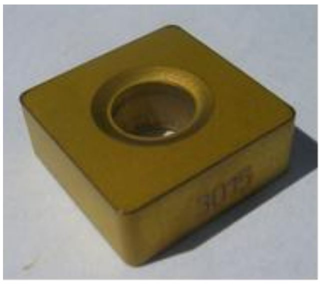


Figure 1: Multilayer coated carbide GC3015 insert.

The lathe used for machining operations was from TOS TRENCIN company; model SN40C, spindle power 6.6 KW.

Surface roughness was measured by a roughness meter (2d) Surf test 201 Mitutoyo.

Table 1: Chemical composition of X38CrMoV5-1.

Composition	(wt. %)
C	0.35
Cr	5.26
Mo	1.19
V	0.5
Si	1.01
Mn	0.32
S	0.002
P	0.016
Other components	1.042
Fe	90.31

3. Experimental results and discussion

Experimental matrix and results of surface roughness criteria (*Ra*, *Rt* and *Rz*) when turning a work material hardened to 50 HRC with multilayer coated carbide GC3015 insert using an orthogonal array ($L_9 = 9$) of the Taguchi method; are shown in Table 2.

3.1. ANOVA for surface roughness

Tables 3, 4 and 5 display the ANOVA for arithmetic mean roughness (*Ra*), total roughness (*Rt*) and mean depth of roughness (*Rz*), respectively. It can be seen that the feed rate is the most major cutting parameters for affecting surface roughness criteria because its increase generates helicoids furrows the result tool shape and helicoid movement tool-workpiece. These furrows are deeper and broader as the feed rate increases. Feed rate contributions on *Ra*, *Rt* and *Rz* are (71.72 , 22.16 and 48.46%). The cutting speed impact on *Ra* is 25.19%, on *Rt* is 38.30% and on *Rz* is 26.10%. As for the depth of cut, its effect on *Ra* is 1.88%, on *Rt* is 31.15% and on *Rz* is 24.09%.

Table 2: Orthogonal array L_9 of surface roughness experimental results.

Parameters							Results		
Parameter levels				Real values			Surface roughness criteria		
Run N°	X_1	X_2	X_3	*Vc*, m/mn	*f*, mm/rev	*ap*, mm	*Ra*, µm	*Rt*, µm	*Rz*, µm
1	-1	-1	-1	50	0.08	0.15	0.66	6.49	4.66
2	-1	0	0	50	0.12	0.30	0.71	7.66	4.78
3	-1	+1	+1	50	0.16	0.45	0.96	5.97	4.96
4	0	-1	0	75	0.08	0.30	0.72	6.26	4.69
5	0	0	+1	75	0.12	0.45	0.73	4.16	3.51
6	0	+1	-1	75	0.16	0.15	1.15	9.43	6.55
7	+1	-1	+1	100	0.08	0.45	0.44	2.70	2.36
8	+1	0	-1	100	0.12	0.15	0.47	3.71	3.07
9	+1	+1	0	100	0.16	0.30	0.91	5.92	5.29

Table 3: ANOVA for Ra.

Source	DF	SS	MS	F-VAL.	P-VAL.	Contr. %
Vc	2	0.1046	0.523	20.92	0.046	25.19
f	2	0.2978	0.1489	59.56	0.017	71.72
ap	2	0.0078	0.0039	1.56	0.391	1.88
Error	2	0.005	0.0025			1.21
Total	8	0.4152				100

Table 4: ANOVA for Rt.

Source	DF	SS	MS	F-VAL.	P-VAL.	Contr. %
Vc	2	13.034	6.517	4.58	0.179	38.30
f	2	7.554	3.777	2.66	0.273	22.16
ap	2	10.603	5.301	3.73	0.211	31.15
Error	2	2.843	1.422			8.39
Total	8	34.034				100

Table 5: ANOVA for Rz.

Source	DF	SS	MS	F-VAL.	P-VAL.	Contr. %
Vc	2	3.3266	1.6633	19.27	0.049	26.10
f	2	6.174	3.087	35.77	0.027	48.46
ap	2	3.0691	1.5346	17.78	0.053	24.09
Error	2	0.1726	0.0863			1.35
Total	8	12.7423				100

3. 2. Surface roughness models

Regression equations for arithmetic mean roughness (*Ra*), total roughness (*Rt*) and mean depth of roughness (*Rz*) were developed based on experimental data. The values of the coefficients involved in the equation were calculated by regression method by using the software's Minitab 15 and Design-Expert 8. Equations (1), (2) and (3) developed for three components of surface roughness (*Ra*, *Rt* and *Rz*) are given below:

$$Ra = 0.455 - 0.0034Vc + 5f - 0.167ap \quad (1)$$

$$Rt = 9.0378 - 0.0519Vc + 24.4583f - 7.5556ap \quad (2)$$

$$Rz = 4.8781 - 0.0246Vc + 21.2083f - 3.8333ap \quad (3)$$

The coefficients of correlation R^2 are (69.1; 69.2 and 67.2) %, respectively.

3. 3. Main effects plot for surface roughness

Figures 2, 3 and 4 show the main effects plot for *Ra*, *Rt* and *Rz*. It can be seen that feed rate is the most important parameter affecting surface finish followed by cutting speed and depth of cut.

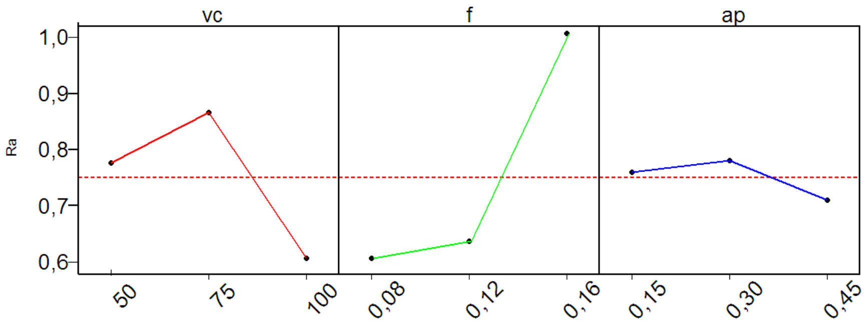


Figure 2: Main effect plot for Ra.

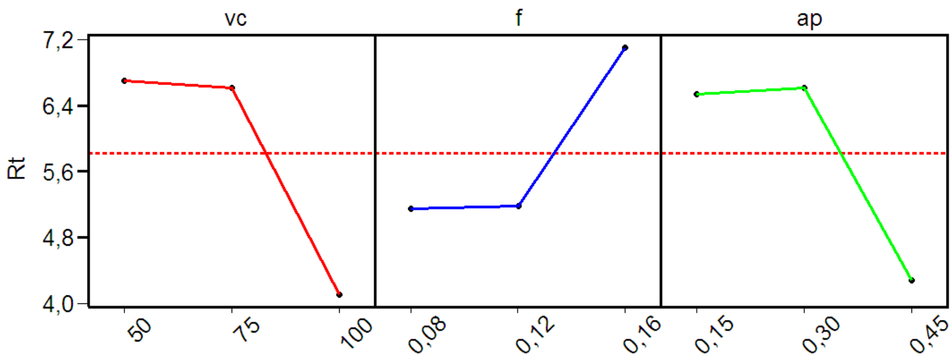


Figure 3: Main effect plot for Rt.

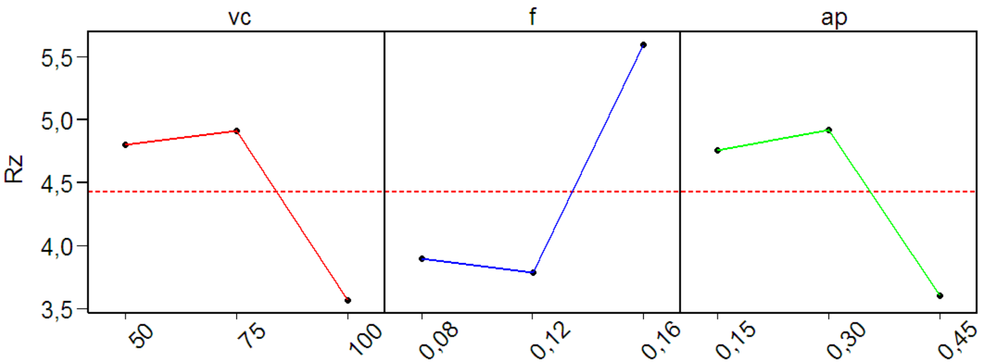
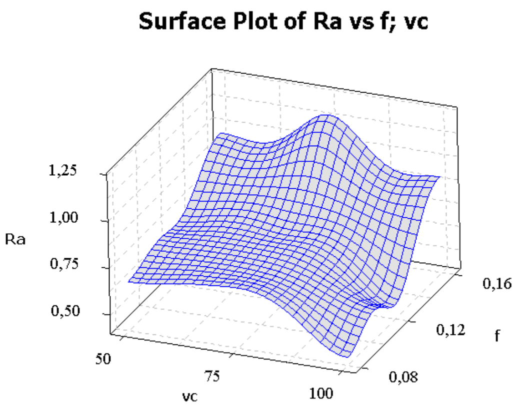


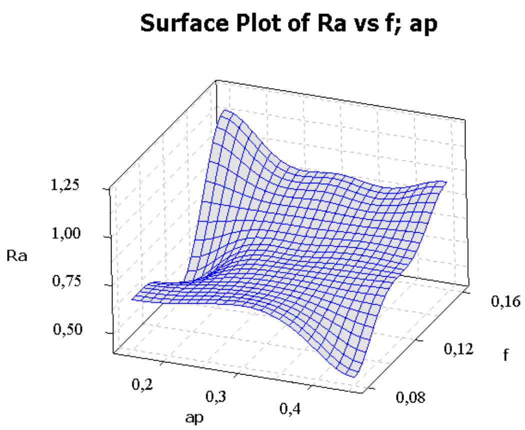
Figure 4: Main effect plot for Rz.

3. 4. 3D Surface plots for surface roughness

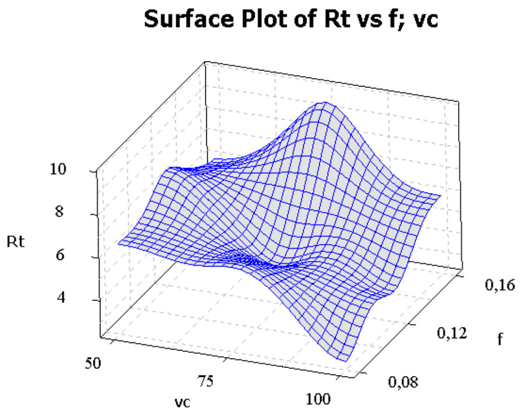
Figures 5 (a, b, c, d, e and f) present 3D surface plots of arithmetic mean roughness (*Ra*), total roughness (*Rt*) and mean depth of roughness (*Rz*). These figures were drawn using response surface methodology (RSM) according to experimental results.



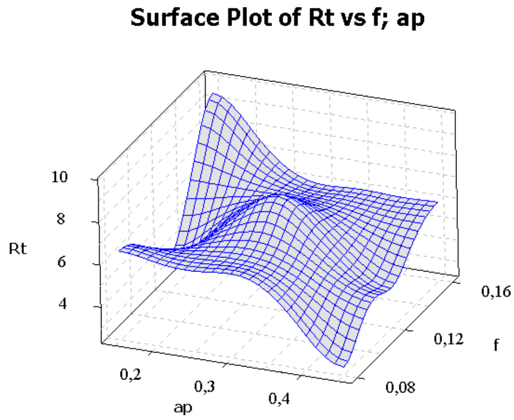
(a)



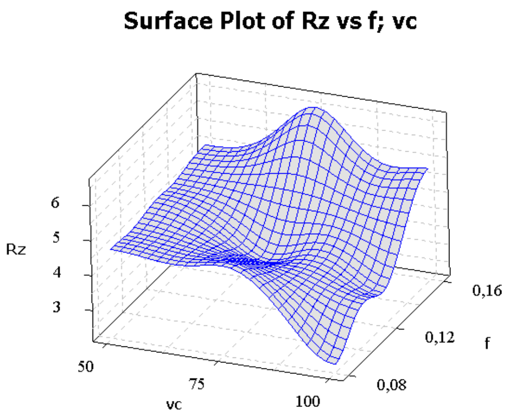
(b)



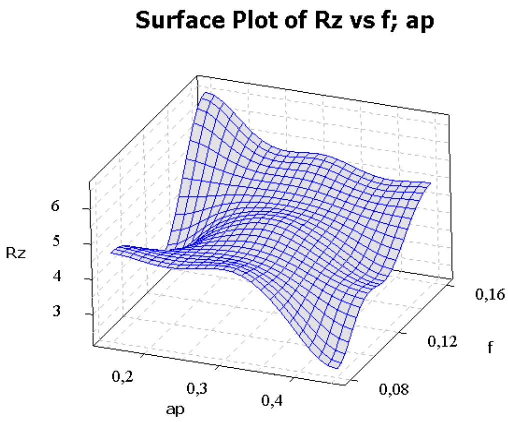
(c)



(d)



(e)

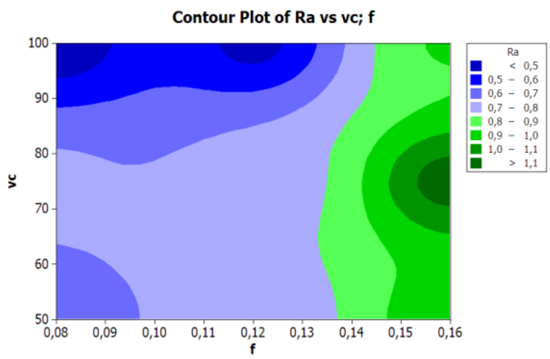


(f)

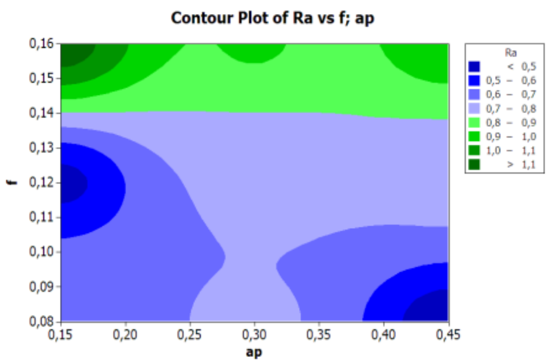
Figure 5: 3D Surface plots of surface roughness.

3.5. Contour plots of surface finish

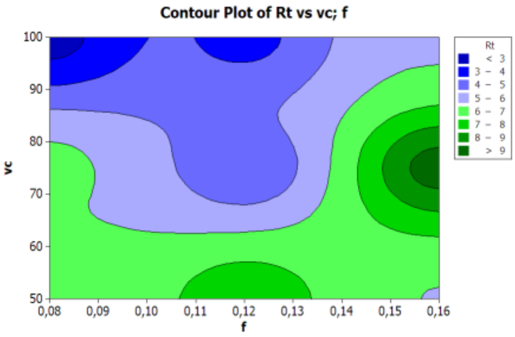
Contour graphs of surface finish *Ra*, *Rt* and *Rz* are plotted in figures 6 (a, b, c, d, e and f). These figures were drawn using response surface methodology (RSM) according to experimental results.



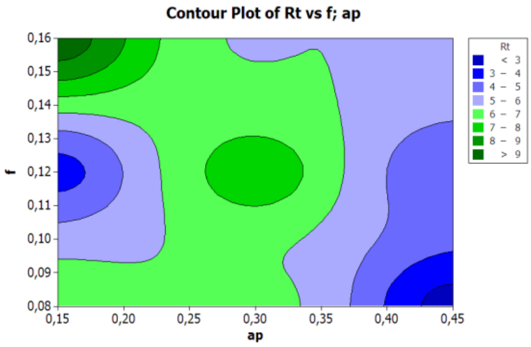
(a)



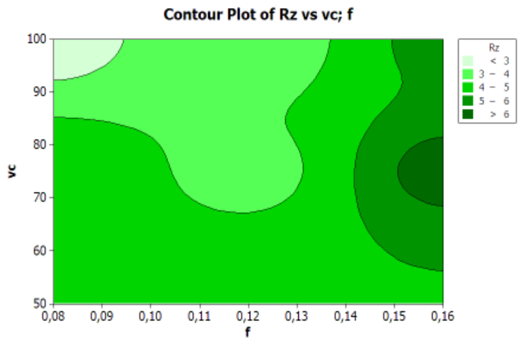
(b)



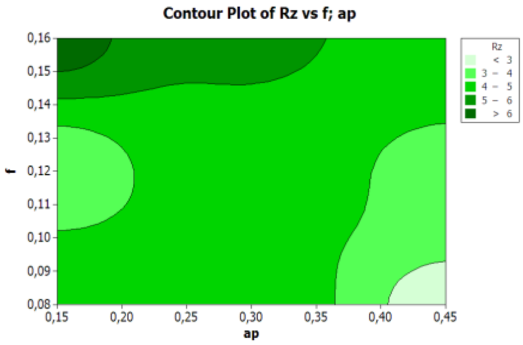
(c)



(d)



(e)



(f)

Figure 6: Contour plots of Ra, Rt and Rz.

4. Conclusion

Based on the experimental results of the present work that was done in dry hard turning of X38CrMoV5-1 high alloy steel treated at 50 HRC machined by multilayer coated carbide GC3015 tool using Taguchi technique, the subsequent conclusions can be derived:

1- Arithmetic mean roughness (*Ra*), total roughness (*Rt*) and mean depth of roughness (*Rz*) get affected mostly by feed rate. Its contributions on *Ra*, *Rt* and *Rz* are (71.72; 22.16 and 48.46%), respectively.

2- The cutting speed impact on *Ra* is 25.19%, on *Rt* is 38.30% and on *Rz* is 26.10%.

3- As for the depth of cut, its effect on surface finish is less important than feed rate and cutting speed. Its contribution on *Ra* is 1.88%, on *Rt* is 31.15% and on *Rz* is 24.09%.

4- Mathematical models would be helpful in selecting cutting variables for optimization of hard cutting process.

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