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Analysis of technological parameters through response surface methodology in machining hardened X38CrMoV5-1 using whisker ceramic tool (Al_2O_3+SiC)

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Abstract. This experimental study is an attempt to model technological parameters such as cutting forces and surface roughness in hard turning of X38CrMoV5-1 hot work tool steel hardened to 50 HRC. This steel is free from tungsten on Cr-Mo-V basis, insensitive to temperature changes and has a high wear resistance. It is employed for the manufacture of helicopter rotor blades and forging dies. The workpiece is machined by a whisker ceramic tool (insert CC670 of chemical composition 75%Al_2O_3+25%SiC) under dry conditions. Based on 3^3 full factorial design, a total of 27 tests are carried out. The range of each parameter is set at three different levels, namely low, medium and high. Mathematical models were deduced by applying analysis of variance (ANOVA) and through factor interaction graphs in the response surface methodology (RSM) in order to express the influence degree of each cutting regime element on cutting force components and surface roughness criteria. The results indicate that the depth of cut is the dominant factor affecting cutting force components. The feed rate influences tangential cutting force more than radial and axial forces. The cutting speed affects radial force more than tangential and axial forces. The results also reveal that feed rate is the dominant factor affecting surface roughness, followed by cutting speed. As for the depth of cut, its effect is not very important. These mathematical models would be helpful in selecting cutting variables for optimization of hard cutting process.

Key words: hard turning, whisker ceramic, X38CrMoV5-1, cutting force, surface roughness, ANOVA, RSM.

1. INTRODUCTION

Hard turning is a cutting process defined as turning materials with hardness higher than 45 HRC under appropriate cutting tools and high cutting speed. Machining of hard steel using advanced tool materials, such as cubic boron nitride and alumina based ceramic, has more advantages than grinding or polishing, such as short cycle time, process flexibility, compatible surface roughness, higher material removal rate and less environment problems without the use of cutting fluid. This process has become a normal practice in industry because it increased productivity and reduced energy consumption [1,2].

Alumina-based ceramics are considered to be one of the most suitable tool materials for machining hardened steels because of their high hot hardness, wear resistance and chemical inertness. However, the ceramic tools possess a high degree of brittleness and low thermal shock resistance which may result in excessive chipping or fracture, thereby reducing tool life. In order to improve their toughness, Al_2O_3-based ceramics are usually reinforced with TiC, TiN, Ti(C, N), SiC, or TiB_2 additions. Alumina, reinforced with SiC whiskers, is the toughest and most resistant to thermal shock of the Al_2O_3-based ceramics. This whisker reinforcement improves the notch resistance of the insert. The end result is a ceramic insert that can run at speeds five to six times that of conventional carbide insert in nickel-based materials. As an added benefit, the toughness of the SiC whiskers also makes this category of ceramic available for machining harder materials with interruptions [3].

Cutting forces and surface finish are the most important technological parameters in machining process. Cutting force is the background for the evaluation of the necessary power machining (choice of the electric motor). It is also used for dimensioning of machine tool components and the tool body. It influences machining system stability. In hard turning, cutting forces have been found to be influenced by a number of factors such as depth of cut, feed rate, cutting speed, cutting time, workpiece hardness, etc. Surface roughness is in relation to many properties of machine elements such as wear resistance, the capacity of fit and sealing. 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 [4].

Theoretical arithmetic mean surface roughness achievable based on tool geometry and feed rate is given approximately as $R_a = 0.032 f^2 / r_\varepsilon$ (f is feed rate and r_ε is the tool nose radius).

The relationship between hardness and cutting forces during turning AISI 4340 steel, hardened from 29 to 57 HRC using mixed alumina tools, was investigated in [5,6]. 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 workpiece hardness increased above 50 HRC, segmented chips were observed and the cutting force showed a sudden elevation.

In machining AISI D2 steel, hardened at 62 HRC with CBN tools, the relationship between forces and cutting regime could be represented by power function type equations [7]. Empirical models were found to correlate the surface finish with the feed rate and cutting speed. The results indicated that the surface roughness increases with the increase of the feed rate, and almost decreases with the increase of cutting speed in the analysis of surface roughness parameters in turning of FRP tubes by PCD tool [8].

Surface roughness has been investigated in finish turning of AISI D2 steels (60 HRC) using ceramic wiper inserts. Experimental results showed that surface roughness R_a values as low as 0.18–0.20 μm are attainable with wiper tools. Better surface finishes were obtained at the lowest feed rate and highest cutting speed combination [9].

The results of the experimental study on turning hardened AISI 4140 steel (63 HRC) with Al_2O_3+TiCN mixed ceramic tools showed that only two interactions, cutting speed–feed rate and feed rate–axial depth of cut, have statically significant influence on the surface roughness: they explain 28% and 23% of the total variation, respectively. An analysis of the interaction plots revealed that in order to minimize the surface roughness, the highest speed, 250 m/min, the lowest level of axial depth of cut, 0.25 mm, and the medium level of feed rate, 0.10 mm/rev, should be preferred. The analysis also showed that setting only the feed rate to its lowest level, 0.05 mm/rev, provides a robust alternative to the aforementioned optimal combination [10].

In hard machining of hardened bearing steel using a cubic boron nitride tool, the radial force is dominating, especially when machining is within the limit of tool nose radius. Such finding is in contradiction with what is known from conventional turning as $F_r = (0.3{-}0.5)F_t$ (here F_r is the radial (thrust) force and F_t is the tangential cutting force). Consequently, the radial force can not be neglected in characterizing the static and dynamic behaviour of such machining system. For the 100Cr6 steel roughness, the machining surface is a function of the local damage form and the wear profile of CBN tool. When augmenting the cutting speed V_c, tool wear increases and leads directly to the degradation of the surface quality. In spite of the evolution of flank wear (*VB*) up to the allowable limit $[VB] = 0.3$ mm, R_a did not exceed 0.55 μm. Roughness is largely influenced by the feed rate under hard turning conditions, although the theoretical model does not describe rationally this effect. Therefore, the use of parametric models may allow better descriptions of roughness phenomena as a function of various factors. A relation between *VB* and R_a in the form $R_a = k\mathrm{e}^{\beta(VB)}$ is proposed. Coefficients k and β vary within the ranges 0.204–0.258 and 1.67–2.90, respectively. It permits the follow-up of tool wear from easily accessible workpiece roughness data [11].

The aim of the present study is to develop statistical models of technological parameters studied for using the main cutting parameters such as cutting speed, feed rate and depth of cut on X38CrMoV5-1 hardened steel. Machining tests were carried out under different conditions with whisker ceramic cutting tool. The predicting equations for cutting force components and surface roughness criteria have been developed. Constants and coefficients of these equations were calculated by applying analysis of variance, multiple linear regression and response surface methodology of softwares Minitab 15 and Design-Expert. However, these models were built using only the main cutting variables (cutting speed, feed rate and depth of cut) and significant interactions. The confirmation experiments, carried out to check the validity of developed models, predicted response factors within 2% error.

2. EXPERIMENTAL PROCEDURE

The material used for experiments is X38CrMoV5-1, hot work tool 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 severe requests in hot dieing, helicopter rotor blades and moulds under pressure. Its chemical composition is given in Table 1.

The workpiece is of 73 mm in diameter and it is machined under dry conditions. It is hardened to 50 HRC. Its hardness was measured by a digital durometer DM2D.

The lathe used for machining operations is TOS TRENCIN, model SN40C, spindle power 6.6 kW. The cutting forces have been measured in real time within the three components (F_a, F_r and F_t) using a quartz KISTLER dynamometer, model 9257 B.

A 2D roughness meter Surftest 201, Mitutoyo, was selected to measure different criteria of surface roughness (arithmetic mean roughness R_a, total roughness R_t and mean depth of roughness R_z). Roughness values were obtained without disassembling the workpiece in order to reduce uncertainties due to resumption operations. These measurements were repeated three times out of three generatrices equally positioned at 120° and the result is an average of these values for a given machining pass.

Table 1. Chemical composition of grade 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

The cutting insert used is a whisker ceramic (CC670), removable, of square form with eight cutting edges and having designation SNGN 120408 T01020. It is mounted on a commercial toolholder of designation CSBNR2525M12 with the geometry of active part characterized by the following angles: $\chi = 75°$, $\alpha = 6°$, $\gamma = -6°$, $\lambda = -6°$ [12]. Here χ is the major cutting edge angle, α is the relief angle, γ is the rake angle and λ is the inclination angle.

Three levels were defined for each cutting variable as given in Table 2. The variable levels were chosen within the intervals, recommended by the cutting tool manufacturer. Three cutting variables at three levels led to a total of 27 tests.

The factors to be studied and the attribution of the respective levels are indicated in Table 3. The first column (C1) of this table was assigned to the cutting speed (V_c), the second (C2) to the feed rate (f) and the fifth (C5) to the depth of cut (a_p). The remaining columns were assigned to interactions.

Table 2. Assignment of the levels to the variables

Level	V_c, m/min	f, mm/rev	a_p, mm
−1 (low)	90	0.08	0.15
0 (medium)	120	0.12	0.30
+1 (high)	180	0.16	0.45

Table 3. Plan of experiments

Tests	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1
2	−1	−1	−1	−1	0	0	0	0	0	0	0	0	0
3	−1	−1	−1	−1	+1	+1	+1	+1	+1	+1	+1	+1	+1
4	−1	0	0	0	−1	−1	−1	0	0	0	+1	+1	+1
5	−1	0	0	0	0	0	0	+1	+1	+1	−1	−1	−1
6	−1	0	0	0	+1	+1	+1	−1	−1	−1	0	0	0
7	−1	+1	+1	+1	−1	−1	−1	+1	+1	+1	0	0	0
8	−1	+1	+1	+1	0	0	0	−1	−1	−1	+1	+1	+1
9	−1	+1	+1	+1	+1	+1	+1	0	0	0	−1	−1	−1
10	0	−1	0	+1	−1	0	+1	−1	0	+1	−1	0	+1
11	0	−1	0	+1	0	+1	−1	0	+1	−1	0	+1	−1
12	0	−1	0	+1	+1	−1	0	+1	−1	0	+1	−1	0
13	0	0	+1	−1	−1	0	+1	0	+1	−1	+1	−1	0
14	0	0	+1	−1	0	+1	−1	+1	−1	0	−1	0	+1
15	0	0	+1	−1	+1	−1	0	−1	0	+1	0	+1	−1
16	0	+1	−1	0	−1	0	+1	+1	−1	0	0	+1	−1
17	0	+1	−1	0	0	+1	−1	−1	0	+1	+1	−1	0
18	0	+1	−1	0	+1	−1	0	0	+1	−1	−1	0	+1
19	+1	−1	+1	0	−1	+1	0	−1	+1	0	−1	+1	0
20	+1	−1	+1	0	0	−1	+1	0	−1	+1	0	−1	+1
21	+1	−1	+1	0	+1	0	−1	+1	0	−1	+1	0	−1
22	+1	0	−1	+1	−1	+1	0	0	−1	+1	+1	0	−1
23	+1	0	−1	+1	0	−1	+1	+1	0	−1	−1	+1	0
24	+1	0	−1	+1	+1	0	−1	−1	+1	0	0	−1	+1
25	+1	+1	0	−1	−1	+1	0	+1	0	−1	0	−1	+1
26	+1	+1	0	−1	0	−1	+1	−1	+1	0	+1	0	−1
27	+1	+1	0	−1	+1	0	−1	0	−1	+1	−1	+1	0

3. RESULTS AND DISCUSSION

Table 4 presents experimental results of cutting force components (F_a, F_r and F_t) and surface roughness criteria (R_a, R_t and R_z) for various combinations of cutting regime elements (cutting speed, feed rate and depth of cut) according to 3^3 full factorial design. The results indicate that cutting forces decrease with increasing cutting speed. This can be related to the temperature increase in cutting zone and leads to the reduction of the yield strength of the workpiece and chip thickness. The results also show that cutting forces increase with increasing feed rate and depth of cut because chip thickness becomes significant what causes the growth of the volume of deformed metal and that requires enormous forces to cut the chip. Minimal values of cutting forces and surface finish were obtained at $V_c = 180$ m/min, $f = 0.08$ mm/rev and a_p = 0.15 mm (test number 19). That means that increasing of cutting speed with lowest feed rate and depth of cut lead to decreasing of cutting force components

Table 4. Design layout and experimental results

Tests	Actual factors			Performance measures					
	V_c, m/min	f, mm/rev	a_p, mm	F_a, N	F_r, N	F_t, N	R_a, µm	R_t, µm	R_z, µm
1	90	0.08	0.15	30.11	92.05	67.28	0.45	2.78	1.70
2	90	0.08	0.30	71.72	128.41	116.93	0.44	2.80	1.81
3	90	0.08	0.45	110.99	176.72	160.84	0.46	3.01	1.89
4	90	0.12	0.15	35.38	108.58	80.19	0.54	3.63	2.16
5	90	0.12	0.30	95.33	155.23	150.62	0.56	3.67	2.21
6	90	0.12	0.45	114.32	204.97	222.74	0.51	3.74	2.30
7	90	0.16	0.15	42.25	139.67	103.36	0.75	4.86	3.94
8	90	0.16	0.30	101.87	201.37	194.47	0.77	4.89	3.97
9	90	0.16	0.45	156.64	264.08	286.85	0.71	4.91	4.06
10	120	0.08	0.15	26.69	84.93	61.09	0.44	2.70	1.60
11	120	0.08	0.30	62.97	121.29	113.58	0.43	2.79	1.69
12	120	0.08	0.45	107.95	170.30	157.94	0.42	2.81	1.75
13	120	0.12	0.15	32.52	100.01	79.28	0.53	3.22	2.14
14	120	0.12	0.30	92.28	144.12	140.59	0.49	3.30	2.19
15	120	0.12	0.45	110.01	171.41	213.32	0.52	3.41	2.25
16	120	0.16	0.15	38.23	128.98	98.74	0.69	4.79	3.87
17	120	0.16	0.30	88.94	198.57	193.13	0.70	4.82	3.90
18	120	0.16	0.45	134.76	214.23	263.26	0.68	4.90	3.99
19	180	0.08	0.15	25.34	77.86	56.92	0.43	2.69	1.58
20	180	0.08	0.30	58.49	117.48	109.93	0.43	2.75	1.63
21	180	0.08	0.45	86.66	168.39	151.40	0.40	2.83	1.72
22	180	0.12	0.15	31.83	95.56	70.08	0.51	3.18	2.11
23	180	0.12	0.30	89.42	139.13	130.06	0.46	3.25	2.22
24	180	0.12	0.45	107.61	170.52	215.50	0.47	3.33	2.24
25	180	0.16	0.15	38.17	125.47	96.45	0.59	4.43	3.67
26	180	0.16	0.30	87.38	187.85	185.87	0.57	4.56	3.71
27	180	0.16	0.45	131.81	211.24	245.96	0.64	4.74	3.78

and surface roughness criteria. Maximal values of cutting force components (F_a, F_r and F_t) and surface roughness criteria (R_a, R_t and R_z) were registered at $V_c = 90$ m/min and $f = 0.16$ mm/rev. In order to achieve better machining system stability and good surface finish, the highest level of cutting speed, 180 m/min, the lowest level of feed rate, 0.08 mm/rev and the lowest level of depth of cut, 0.15 mm, should be recommended.

3.1. ANOVA for F_a, F_r and F_t

The results of analysis of variance (ANOVA) for axial force F_a, radial force F_r and tangential cutting force F_t are respectively shown in Tables 5, 6 and 7.

Table 5. ANOVA for F_a

Source	*DF*	*SS*	*MS*	*F*	*P*	*C*, %
V_c	2	590.0	295.0	20.59	0.001	1.56
F	2	3 181.8	1 590.9	111.05	<0.001	8.42
A_p	2	32 448.5	16 224.2	1 132.50	<0.001	85.84
$V_c \times f$	4	140.3	35.1	2.45	0.131	0.37
$V_c \times a_p$	4	162.4	40.6	2.83	0.098	0.43
$f \times a_p$	4	1 164.3	291.1	20.32	<0.001	3.08
Error	8	114.6	14.3			0.30
Total	26	37 801.9				100

Table 6. ANOVA for F_r

Source	*DF*	*SS*	*MS*	*F*	*P*	*C*, %
V_c	2	1 925.8	962.9	17.30	0.001	3.42
f	2	16 822.0	8 411.0	151.14	<0.001	29.90
a_p	2	35 568.8	17 784.4	319.58	<0.001	63.23
$V_c \times f$	4	239.8	59.9	1.08	0.428	0.43
$V_c \times a_p$	4	557.6	139.4	2.50	0.125	0.99
$f \times ap$	4	693.2	173.3	3.11	0.080	1.24
Error	8	445.2	55.6			0.79
Total	26	56 252.3				100

Table 7. ANOVA for F_t

Source	*DF*	*SS*	*MS*	*F*	*P*	*C*, %
V_c	2	815.1	407.6	8.74	0.010	0.73
f	2	25 166.4	12 583.2	269.76	<0.001	22.62
a_p	2	80 618.8	40 309.4	864.16	<0.001	72.46
$V_c \times f$	4	75.3	18.8	0.40	0.801	0.07
$V_c \times a_p$	4	94.8	23.7	0.51	0.732	0.09
$f \times a_p$	4	4 115.3	1 028.8	22.06	<0.001	3.70
Error	8	373.2	46.6			0.33
Total	26	111 258.9				100

These tables also show the degrees 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 and different interactions. A low *P* value (≤0.02) indicates statistical significance for the source on the corresponding response.

It is clear from the results of ANOVA that the depth of cut affects F_a in a considerable way. Its contribution is 85.84%. The second factor influencing F_a is feed rate. Its contribution is 8.42%. As for cutting speed, its effect is less important and its contribution is 1.56%. The interaction $f \times a_p$ is significant. Its contribution is 3.08%. The interactions $V_c \times f$ and $V_c \times a_p$ are not significant.

Respectively, their contributions are 0.37% and 0.43%. It can be seen that the depth of cut is the most important factor affecting radial force F_r. Its contribution is 63.23%. The second factor influencing F_r is feed rate. Its contribution is 29.90%. As for the cutting speed, its contribution is 3.42%. The interactions $V_c \times f$, $V_c \times a_p$ and $f \times a_p$ are not significant. Respectively, their contributions are 0.43%, 0.99% and 1.24%. It can be noted that the depth of cut is the dominant factor affecting tangential cutting force F_t. Its contribution is 72.46%. The second factor influencing F_t is feed rate. Its contribution is 22.62%. As for the cutting speed, its effect is less significant because its contribution is 0.73%. The interaction $f \times a_p$ is significant. Its contribution is 3.70%. The interactions $V_c \times f$ and $V_c \times a_p$ are not significant. Respectively, their contributions are 0.07% and 0.09%. These results are close to those found in [[13–21]]. The difference is the hardness of machined steel, its chemical composition and its mechanical characteristics. For this cutting regime ($0.12 \le f \le 0.16$ mm/rev and $a_p =$ 0.45 mm), we confirm that the tangential cutting force becomes the major force.

To understand the hard turning process in terms of cutting forces, mathematical models were developed using the multiple regression method. F_a, F_r and F_t models are successively given by Eqs (1), (2) and (3). Respectively, their coefficients of correlation R^2 are 95.48%, 93.02% and 98.9%.

$$F_a = 9.67 - 0.12V_c - 5.79f + 146.40a_p + 1126.39fa_p\,, \tag{1}$$

$$F_r = -0.145 - 0.199V_c + 741.708f + 295.8334a_p\,, \tag{2}$$

$$F_t = 26.04 - 0.14V_c + 47.63f + 91.70a_p + 2953.19fa_p\,. \tag{3}$$

3.2. Main effects plot for F_a, F_r and F_t

Figures 1, 2 and 3 give the main factor plots for F_a, F_r and F_t. Cutting forces appear to be decreasing functions of V_c. These figures also indicate that F_a, F_r and F_t are almost linear increasing functions of a_p and f.

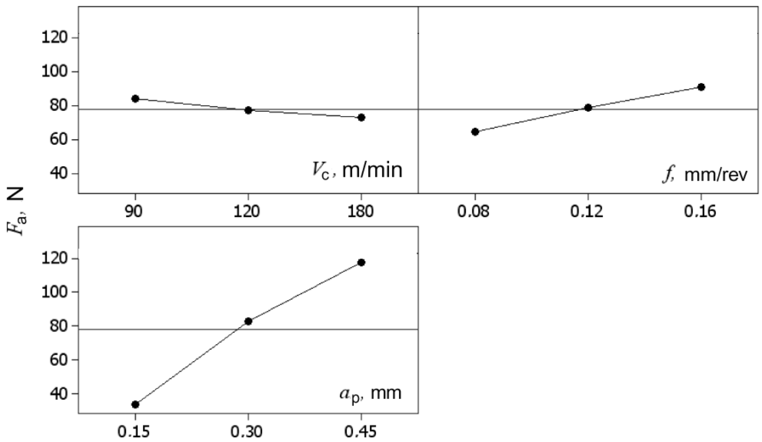

Fig. 1. Main effects plot for F_a.

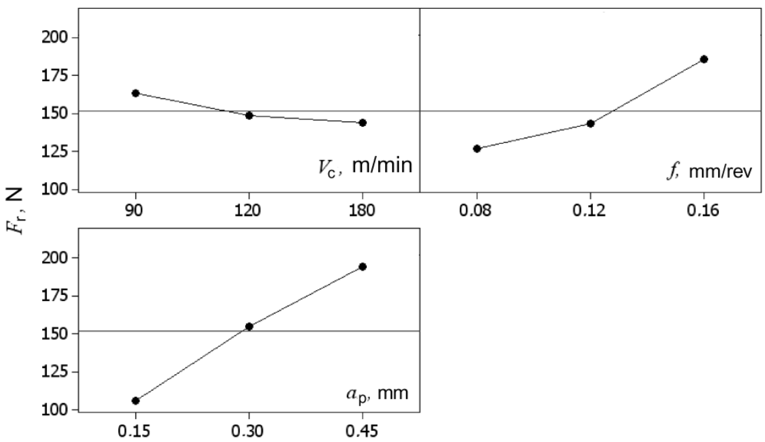

Fig. 2. Main effects plot for F_r.

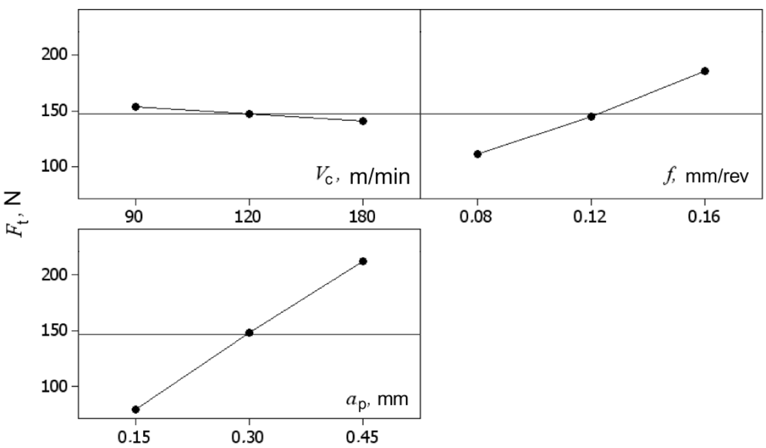

Fig. 3. Main effects plot for F_t.

3.3. 3D Surface plots of F_a, F_r and F_t

3D Surface plots of F_a, F_r and F_t vs. different combinations of cutting regime elements are shown in Fig. 4. These figures were obtained using response surface methodology according to their mathematical models.

3.4. ANOVA for R_a, R_t and R_z

The results of analysis of variance for roughness criteria R_a, R_t and R_z are respectively shown in Tables 8, 9 and 10. It is clear from the results of ANOVA that the feed rate is the dominant factor affecting surface finish. Its contribution on R_a is 85.70%, on R_t 96.57% and on R_z 98.95%. The second factor, influencing R_a, R_t and R_z, is cutting speed. Its contribution on R_a is 8.12%, on R_t 1.91% and on R_z 0.45%. As for the depth of cut, its contribution is not important. The interaction $V_c \times f$ is significant on R_t and R_z but interactions $V_c \times a_p$ and $a_p \times f$ are not significant on surface roughness criteria.

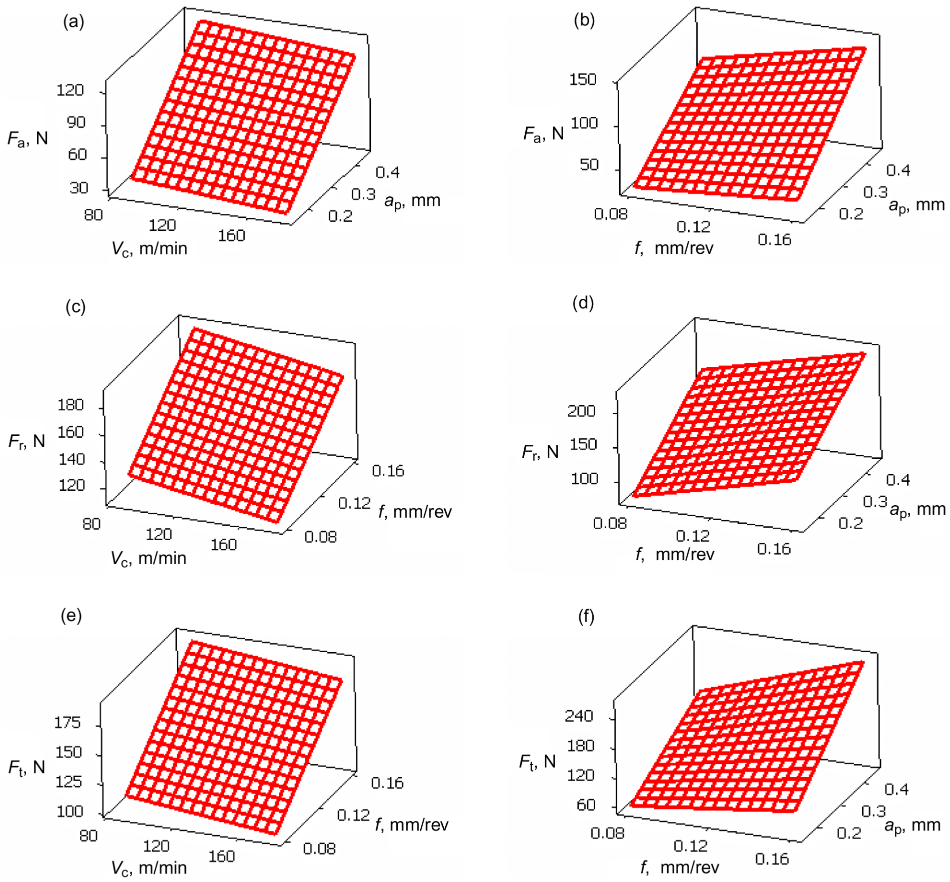

Fig. 4. 3D Surface plots of cutting forces.

Table 8. ANOVA for R_a

Source	*DF*	*SS*	*MS*	*F*	*P*	*C*, %
V_c	2	0.026674	0.013337	18.23	0.001	8.12
f	2	0.281341	0.140670	192.31	<0.001	85.70
a_p	2	0.000830	0.000415	0.57	0.588	0.25
$V_c \times f$	4	0.011081	0.002770	3.79	0.052	3.38
$V_c \times a_p$	4	0.001793	0.000448	0.61	0.665	0.55
$a_p \times f$	4	0.000726	0.000181	0.25	0.903	0.22
Error	8	0.005852	0.000731			1.78
Total	26	0.328296				100

Table 9. ANOVA for R_t

Source	*DF*	*SS*	*MS*	*F*	*P*	*C*, %
V_c	2	0.3616	0.1808	58.64	<0.001	1.91
f	2	18.2904	9.1452	2966.01	<0.001	96.57
a_p	2	0.1106	0.0553	17.93	0.001	0.58
$V_c \times f$	4	0.1476	0.0369	11.96	0.002	0.78
$V_c \times a_p$	4	0.0056	0.0014	0.46	0.766	0.03
$a_p \times f$	4	0.0002	0.0001	0.02	0.999	0.01
Error	8	0.0247	0.0031			0.12
Total	26	18.9407				100

Table 10. ANOVA *for* R_z

Source	*DF*	*SS*	*MS*	*F*	*P*	*C*, %
V_c	2	0.1059	0.529	178.09	<0.001	0.45
f	2	23.2570	11.6285	39 123.85	<0.001	98.95
a_p	2	0.0815	0.0407	137.08	<0.001	0.35
$V_c \times f$	4	0.0542	0.0136	45.63	<0.001	0.23
$V_c \times a_p$	4	0.0008	0.0002	0.65	0.640	0.00
$a_p \times f$	4	0.0028	0.0007	2.32	0.145	0.01
Error	8	0.0024	0.0003			0.01
Total	26	23.5045				100

Models of R_a, R_t and R_z are given by Eqs (4), (5) and (6). Their coefficients of correlation R^2 are 88.9%, 93.87% and 89.25%, respectively:

$$R_a = 0.29571 - 0.00084V_c + 3.05556f - 0.04444a_p, \tag{4}$$

$$R_t = 0.4347 + 0.0009V_c + 28.7530f + 0.5185a_p - 0.0316V_c f, \tag{5}$$

$$R_z = -0.8639 + 0.0006V_c + 29.4970f + 0.4481a_p - 0.0184V_c f. \tag{6}$$

3.5. Main effects plot for R_a, R_t and R_z

Figures 5, 6 and 7 give the main factor plots for R_a, R_t and R_z. Surface roughness appears to be a decreasing function of cutting speed V_c. These figures also indicate that R_a, R_t and R_z are increasing functions of the feed rate f.

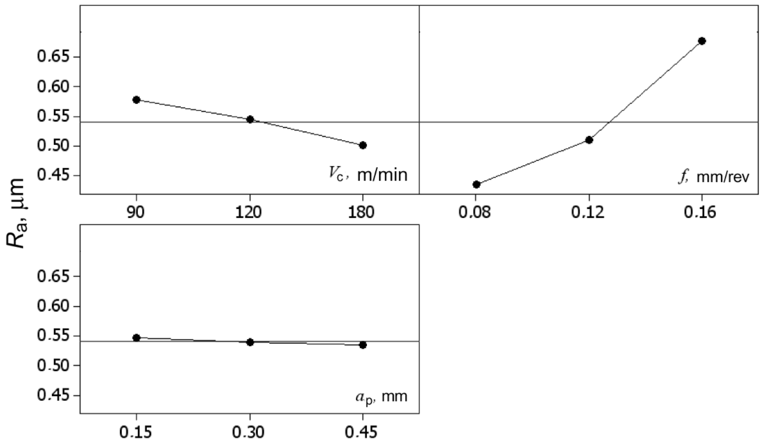

Fig. 5. Main effects plot for R_a.

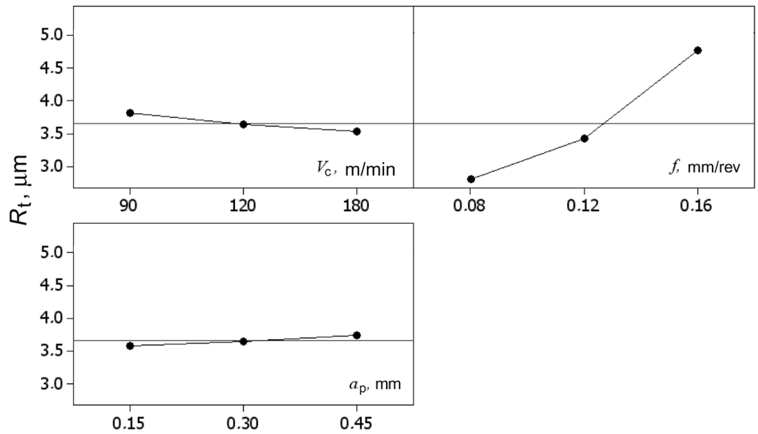

Fig. 6. Main effects plot for R_t.

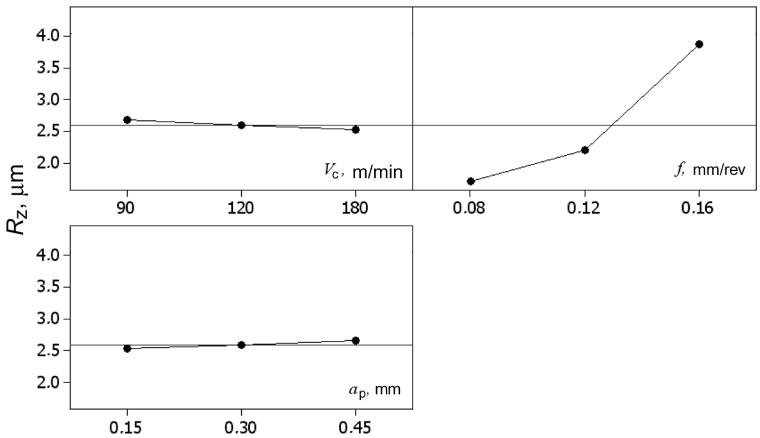

Fig. 7. Main effects plot for R_z.

3.6. 3D Surface plots of R_a, R_t and R_z

The 3D Surface plots of R_a, R_t and R_z vs. different combinations of cutting regime elements are shown in Fig. 8. These figures were obtained according to their respective mathematical models and using the response surface methodology.

4. CONCLUSIONS

The tests of straight turning carried out on grade X38CrMoV5-1 steel treated at 50 HRC, machined by a whisker ceramic tool (insert CC670) enabled us to develop statistical models of cutting force components and surface roughness criteria. These models were obtained by softwares Minitab 15 and Design-Expert using multiple linear regression and response surface methodology.

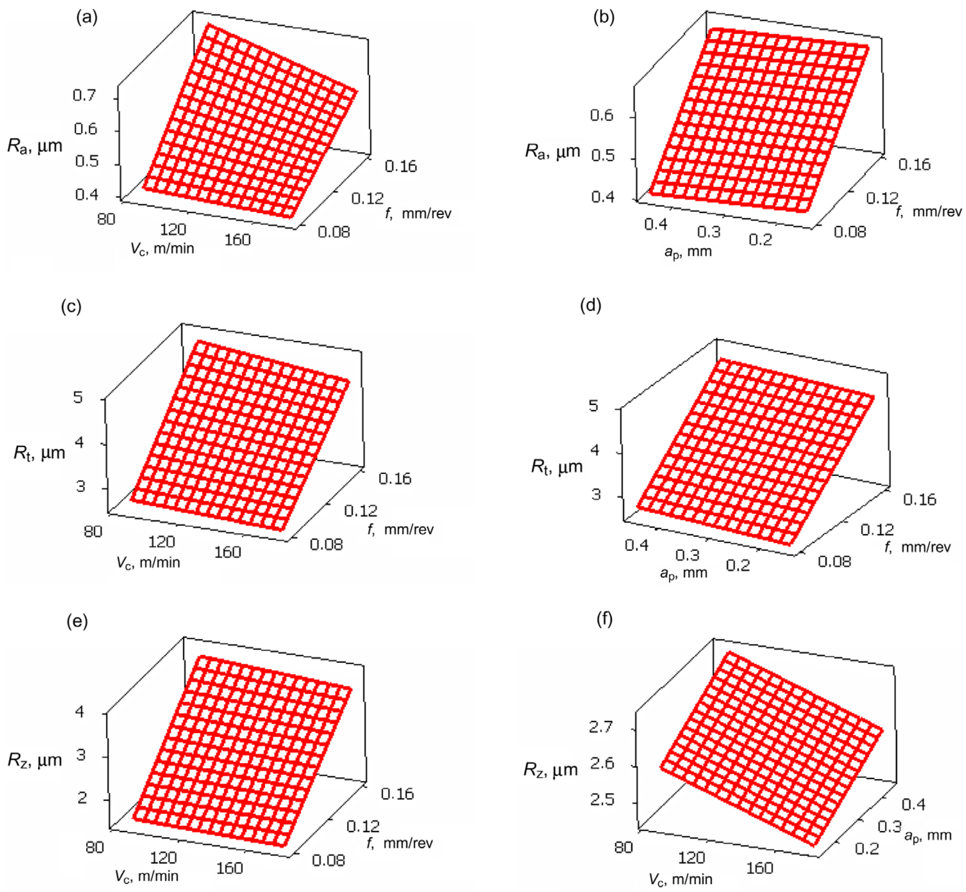

Fig. 8. 3D Surface plots of roughness.

The results revealed that the depth of cut seems to influence cutting forces more significantly than the feed rate and cutting speed. The results also indicated that the feed rate is the dominant factor affecting surface roughness, followed by cutting speed. As for the depth of cut, its effect is not very important. Thus, if we want to get good machining system stability, much removed amount of chip and good surface finish, we must use the highest level of cutting speed, 180 m/min, the lowest level of feed rate, 0.08 mm/rev and the medium level of depth of cut, 0.30 mm.

Statistical models deduced defined the degree of influence of each cutting regime element on cutting force components and surface roughness criteria. They can also be used for optimization of the hard machining. This is a very significant issue for automated monitoring of industrial processes.

This study reveals that in dry hard turning of this steel and for all cutting conditions tested, the principal force is not always the radial force. For this cutting regime ($0.12 \le f \le 0.16$ mm/rev and $a_p = 0.45$ mm), the tangential cutting force becomes the major force, followed by radial and axial forces. This study confirms that in dry hard turning of this steel and for all cutting conditions tested, the found roughness criteria are close to those obtained in grinding ($0.4 \le R_a < 0.78$ µm).

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Tehnoloogiliste parameetrite analüüs karastatud tööriistaterase X38CrMoV5-1 treimisel niitmonokristallidega armeeritud keraamilise (Al_2O_3+SiC) lõikeriistaga

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Käesolevas eksperimentaalses uurimuses on modelleeritud lõiketöötluse peamisi parameetreid (lõikejõu komponendid ja pinnakareduse parameetrid) kõvaduseni 50 HRC karastatud kuumstantsiterase X38CrMoV5-1 treimisel. Kulumiskindel Cr-Mo-V tööriistateras on volframivaba, ei ole tundlik temperatuurimuutustele ja leiab kasutamist helikopteritiivikute ning stantside valmistamisel. Kuumstantsiterast treiti monokristallidega armeeritud Al_2O_3 baasil keraamiliste (75% Al_2O_3 + 25% SiC) lõiketeradega jahutusvedelikku kasutamata. Eksperimentide kavandamisel kasutati täisfaktoriaalset planeerimismeetodit. Kokku tehti 27 katset iga uuritava faktori (lõikekiirus, ettenihkekiirus, lõikesügavus) kolmel erineval tasandil. Analüüsiti eelnimetatud tehnoloogiliste faktorite mõju lõikejõu kolmele komponendile ja pinnakaredust iseloomustavatele parameetritele.

Uurimistulemused näitasid, et domineeriva mõjuga lõikejõu komponentidele on lõikesügavus. Ettenihkekiirus on suurima mõjuga lõikejõu tangentsiaalkomponendile, väiksem radiaal- ja aksiaalkomponendile. Lõikekiiruse mõju on suurim lõikejõu radiaalkomponendile, väiksem tangentsiaal- ja aksiaalkomponendile. Tulemused näitavad samuti, et pinnakaredust mõjutab kõige rohkem ettenihkekiirus. Vähim mõju on lõikesügavusel. Uurimistöö tulemusena saadud matemaatilised mudelid on abiks lõiketöötlusparameetrite valikul suure kõvadusega tööriistateraste treimisel rasketes lõiketingimustes.