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Modeling and optimization of hard turning of X38CrMoV5-1 steel with CBN tool: Machining parameters effects on flank wear and surface roughness †

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Abstract

The present study, aims to investigate, under turning conditions of hardened AISI H11 (X38CrMoV5-1), the effects of cutting parameters on flank wear (*VB*) and surface roughness (*Ra*) using CBN tool. The machining experiments are conducted based on the response surface methodology (RSM). Combined effects of three cutting parameters, namely cutting speed, feed rate and cutting time on the two performance outputs (i.e. *VB* and *Ra*), are explored employing the analysis of variance (ANOVA). Optimal cutting conditions for each performance level are established and the relationship between the variables and the technological parameters is determined using a quadratic regression model. The results show that the flank wear is influenced principally by the cutting time and in the second level by the cutting speed. Also, it is that indicated that the feed rate is the dominant factor affecting workpiece surface roughness.

Keywords: Hard turning; Flank wear; Surface roughness; CBN; RSM; ANOVA

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1. Introduction

In the past ten years, research and development of new tool materials, such as Polycrystalline Cubic Boron Nitride (PCBN), made precision hard turning possible for work pieces with hardness in the range 58-62 HRC. Compared to grinding operations, precision hard turning enabled relatively high material removal rate and flexibility and thus, became more attractive especially to automotive, bearing and hydraulic industries [1-3]. Huang et al. presented a thorough review that discusses CBN tool material microstructure, encountered wear patterns and tool wear rate modeling under hard turning [4]. They also stated that high cutting speed and interaction between the binder in PCBN tool and steel constituents occurred [5]. Dureja et al. applied the response surface methodology (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 [6].When turning hardened 100Cr6, Banga and Abrão found that cutting speed is the most factor influencing tool life. These authors have shown that PCBN cutting tools provide longer tool life than both mixed and composite ceramics [7]. In addition, the superiority of CBN tools for hard materials machining was also illustrated in the study performed by Lima et al. on the turning of AISI 4340 (48 HRC) steel when considering a series of PCBN and coated carbides tools [8]. A model built to evaluate the machinability of Hadfield steel using RMS and ANOVA techniques was presented by Horng et al. The study revealed that the flank wear is influenced by the cutting speed while the interaction effect of the feed rate with the nose radius and the corner radius of the tool have statistical significance on obtained surface roughness [9]. In an earlier investigation, Asina et al. employed the Taguchi technique and ANOVA in order to optimize surface roughness for mixed ceramic (Al_2O_3+T_iC) tools [10]. They found that tool nose shape design affects drastically both surface finish and productivity in finish hard turning processes. Sahin and Motorcu [11] study revealed that the feed rate was the main factor influencing the surface roughness. It increases with feed rate and dropped off with increasing the cutting speed and the depth of cut, respectively. Very recently, the effects of machining parameters (i.e. cutting speed, feed rate and depth of cut) on surface roughness and cutting forces during machining of AISI 52100 steel with CBN tool were investigated by Bouacha et al. using a three

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level factorial design (3^3). Results showed how much surface roughness is mainly influenced by feed rate and cutting speed and the depth of cut exhibited maximum effect on the cutting forces [12]. Neseli et al. [13] applied response surface methodology (RSM) to optimize the effect of tool geometry parameters on surface roughness in hard turning of AISI 1040 with P25 tool. Yallese et al. found that a cutting speed of 120 m/min is an optimal value for machining X200Cr12 using CBN7020 [14]. 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, 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 [15]. The best surface roughness is obtained with CBN tools followed by mixed ceramic and then the carbide tools. Based on the ANOVA outcomes, the contributions of the hard turning parameters on surface roughness followed the order (1) cutting tool type, (2) feed rate, (3) workpiece hardness, (4) cutting speed and (5) depth of cut [16].

The current study investigates the influence of cutting parameters (cutting speed, feed rate and cutting time) in relation to flank wear (*VB*) and surface roughness (*Ra*) on machinability. The processing conditions are turning of hardened hot work steel (AISI H11) with CBN tools using both response surface methodology (RSM) and ANOVA. 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, only the significant parameters will be used to develop mathematical models using response surface methodology (RSM). The latter is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which response of interest is influenced by several variables and the objective is to optimize the response.

2. Experimental procedure

Turning experiments were performed in dry conditions using lathe type SN 40C with 6.6 KW spindle power. The workpiece material was AISI H11, hot work steel which is popularly used for the manufacture of highly stressed diecasting moulds and inserts with high tool life expectancy, plastic moulds subject to high stress, helicopter rotor blades and forging dies. 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 SNGA12 04 08 S01020 and is manufactured by Sandvik. The physical properties of the CBN7020 tool are summarized in Table 2.

Table 1. Chemical composition of AISI H11 steel.

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

Table 2. Physical properties of CBN7020 tool.

Material	CBN 7020
Hardness HV (daN/mm^2)	2800
Tenacity (MPa m$^{1/2}$)	4.2
Young's modulus (GPa)	570
Density (g/cm^3)	4.3
Grain size (μm)	2.5

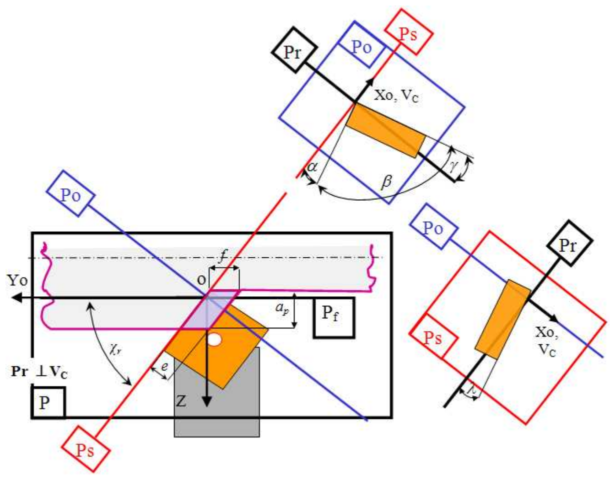

Fig. 1. Illustration of cutting tool geometry.

Tool holder is codified as PSBNR25×25M12 with a common active tool part geometry described by χ_r = +75°, λ = -6°, γ = -6° and α = +6 as shown in Fig. 1. Wear is measured using a HUND optical microscope (W-AD) equipped with CCD camera. Instantaneous roughness criteria measurements (*Ra*), for each cutting condition, are obtained by means of a Mitutoyo Surftest 201 roughness meter. The length examined is 2.4 mm with a basic span of 3. The measured values of *Ra* are within the range 0.05 to 40 μm. Absolute roughness is directly measured on the same turned part, without disassembling, in order to reduce uncertainties due to resumption operations. The measurements are repeated 3 times at 3 reference lines equally positioned at 120° and the result is an average of these values for given machining pass

Table 3. Assignment of the levels to the factors.

Level	Cutting speed (m/min)	Feed rate (mm/rev)	Cutting time (min)
1	120	0.08	7
2	180	0.12	14
3	240	0.16	21

3. Design of experiments

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 [17]. 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 machinability aspect is given as:

$$Y = \phi(Vc, f, t) \quad (1)$$

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

$$Y = a_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i,j}^{k} b_{ij} X_i X_j + \sum_{i=1}^{k} b_{ii} X_i^2 \quad (2)$$

where b_0 is the free term of the regression equation, the coefficients b_1, b_2, $\cdots$, b_k and b_{11}, b_{22}, $\cdots$, b_{kk} are the linear and the quadratic terms respectively; while b_{12}, b_{13}, $\cdots$, $b_{1\text{-}k}$ are the interacting terms. The experimental plan is developed to assess the influence of cutting speed (*Vc*), feed rate (*f*) and cutting time (*t*) on the flank wear (*VB*) and surface roughness (*Ra*). Three levels are defined for each cutting variable as given in Table 3 (*VB* and *Ra*). 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.

4. Results and discussion

4.1 Cutting parameters effects on flank wear and surface roughness

Table 4 presents the cutting conditions (cutting speed, feed rate and cutting time) and corresponding experimental results of flank wear (*VB*) and surface roughness (*Ra*) after turning AISI H11 steel, using a CBN tool.

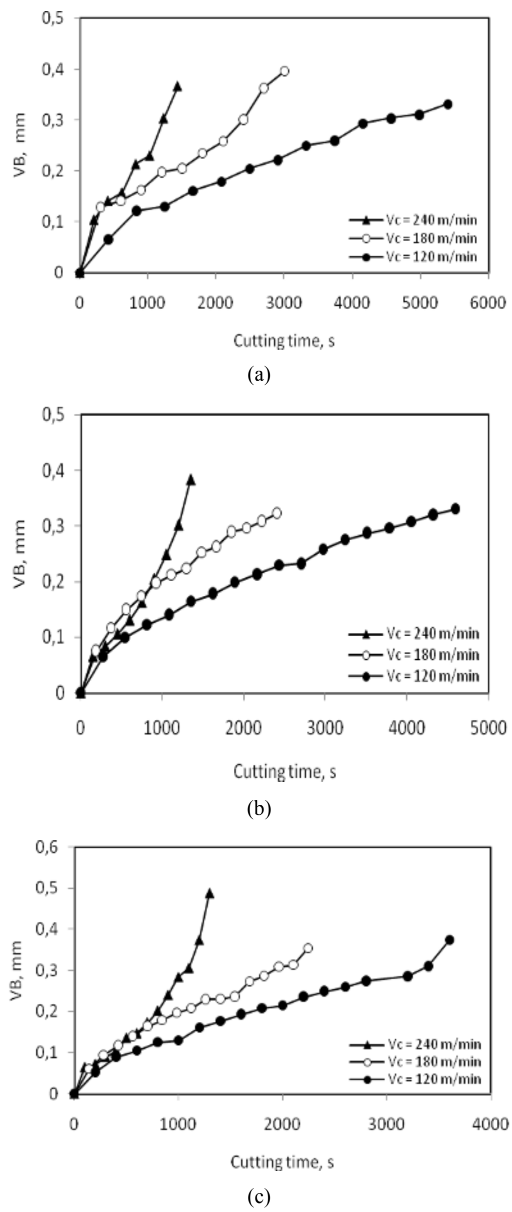

Fig. 2. Effect of cutting time on flank wear for: (a) f = 0.08 mm/rev; (b) f = 0.12 mm/rev; (c) f = 0.16 mm/rev.

Fig. 2 shows the flank wear (*VB*) evolution as cutting time elapses for distinct cutting speeds and feed rates. As expected, *VB* increases with cutting time, cutting speed and feed rate, however, a drastic increase in flank wear is observed when turning at a cutting speed 240 m/min and feed rate 0.16 mm/rev. Additionally, for a feed rate of 0.16 mm/rev, *VB* presented considerable higher values at *Vc* = 240 m/min when compared to 120 and 180 m/min.

The micrographs of flank wear at three cutting speeds and three feed rates are presented in Fig. 4. We can see that the flank wear evolution is regular.

Table 4. Experimental results for *VB* and *Ra*.

Test number	*Vc*, m/min	*f*, mm/rev	*t*, min	*VB*, mm	*Ra*, µm
1	120	0.08	7	0.066	0.263
2	120	0.08	14	0.124	0.295
3	120	0.08	21	0.130	0.315
4	120	0.12	7	0.082	0.820
5	120	0.12	14	0.122	0.838
6	120	0.12	21	0.156	0.888
7	120	0.16	7	0.092	0.572
8	120	0.16	14	0.126	0.748
9	120	0.16	21	0.165	0.874
10	180	0.08	7	0.134	0.218
11	180	0.08	14	0.160	0.274
12	180	0.08	21	0.200	0.347
13	180	0.12	7	0.118	0.395
14	180	0.12	14	0.188	0.432
15	180	0.12	21	0.201	0.494
16	180	0.16	7	0.118	0.751
17	180	0.16	14	0.179	0.813
18	180	0.16	21	0.229	0.901
19	240	0.08	7	0.141	0.249
20	240	0.08	14	0.218	0.222
21	240	0.08	21	0.310	0.280
22	240	0.12	7	0.100	0.976
23	240	0.12	14	0.186	1.200
24	240	0.12	21	0.327	1.440
25	240	0.16	7	0.102	0.830
26	240	0.16	14	0.220	1.359
27	240	0.16	21	0.316	2.240

Table 5. Analysis of variance for *VB*.

Source	DF	SC sq.	MS	F-value	Prob > F	Cont. %
Vc	1	0.041	0.041	135.84	< 0.0001	32.35
f	1	2.276E-4	2.276E-4	0.76	0.3962	0.18
t	1	0.065	0.065	216.14	< 0.0001	51.47
Vc × *f*	1	7.363E-4	7.363E-4	2.45	0.1358	0.58
Vc × *t*	1	0.013	0.013	44.17	< 0.0001	10.52
f × *t*	1	8.167E-4	8.167E-4	2.72	0.1175	0.65
Vc×*Vc*	1	9.335E-5	9.335E-5	0.31	0.5845	0.08
f × *f*	1	9.074E-5	9.074E-5	0.30	0.5897	0.07
t × *t*	1	6.446E-5	6.446E-5	0.21	0.6491	0.05
Error	17	5.106E-3	3.004E-4			4.05
Total	26	0.126				100

4.2 ANOVA for VB

The results of variance analysis (ANOVA) for flank wear (*VB*) are shown in Table 5. The analysis is carried out for a significance level $\alpha = 0.5$, (i.e. for a confidence level of 95%). In this table, the degrees of freedom (DF), sum of squares (SC sq.), mean square (MS), F-values and probabilities (P-value), in addition to the contribution (Cont. %) of each factor, are also shown.

It is observed that the parameters cutting time (Cont. =

Table 6. Analysis of variance for *Ra*.

Source	DF	SC sq.	MS	F-value	Prob > F	Cont. %
Vc	1	0.661	0.546	17.239	0.0007	11.88
f	1	2.245	0.661	58.497	< 0.0001	40.32
t	1	0.491	2.245	12.794	0.0023	8.81
Vc × *f*	1	0.363	0.491	9.475	0.0068	6.53
Vc × *t*	1	0.255	0.363	6.657	0.0195	4.58
f × *t*	1	0.159	0.255	4.147	0.0576	2.85
Vc×*Vc*	1	0.545	0.159	14.211	0.0015	9.79
f × *f*	1	0.183	0.545	4.778	0.0431	3.29
t × *t*	1	0.010	0.183	0.038	0.6048	0.19
Error	17	0.652	0.010			11.71
Total	26	5.567				100

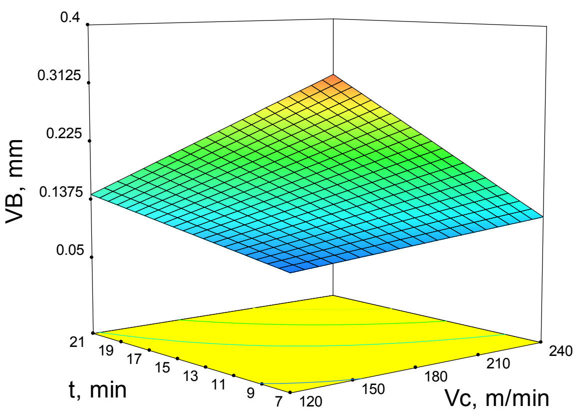

Fig. 3. Effect of cutting speed and cutting time on flank wear.

51.47%), cutting speed (32.35%) and the interaction *Vc×t* (Cont. = 10.52%) have a great influence on the flank wear, especially the cutting time. The interactions *Vc×f, f×t, Vc×Vc, t×t, f×f* and the feed rate factor do not present any significant contribution on the obtained tool wear.

The effect of cutting speed and cutting time on the flank wear is shown in Fig. 3. It is found that tool wear increases with increasing effects of both cutting time and speed. This figure also displays that the tool wear increase with the increase of the cutting time.

4.3 ANOVA for the surface roughness (Ra)

It is clear from the results of ANOVA that the feed rate is the dominant factor affecting surface finish *Ra* (Table 6). Its contribution is 40.32%. The second factor influencing *Ra* is the cutting speed. Its contribution is 11.88%. As for the cutting time, its contribution is 8.81%. The interaction cutting time/cutting time do not present a statistical significance on the arithmetic mean roughness (*Ra*).

Fig. 5 shows the estimated response surface for the machined surface roughness (*Ra*) in relationship with cutting speed (*Vc*) and feed rate. As it can be seen from this figure, the roughness (*Ra*) tends to increase, considerably with increase in feed rate (*f*). This figure also displays that the surface roughness (*Ra*) is characterized by three distinct zones according to the cutting speed evolution.

The first zone where the cutting speed varies from 120 to 150 m/min corresponds to a decrease in roughness (*Ra*).The second zone is characterized by an interval where the surface roughness is stabilized according to the drop in the cutting forces that translate a relative of machining system [14]. The third zone starts when the cutting speed *Vc*, is greater than 190 m/min. In this location, the surface roughness takes an ascending evolution because of dynamic vibrations. The optimal surface roughness is achieved with the combination of lowest feed rate and middle cutting speed, as reported by earlier investigators.

The effect of cutting speed and cutting time on the surface roughness is shown in Fig. 6. This figure displays that the value of surface roughness increases with the increase of cutting time. Also, the higher is the cutting time, the higher is the friction between tool-workpiece. Consequently, this involves an increase in temperature and tool wear [14-17].

Finality, Fig. 7 shows via ANOVA results that the effect of cutting time and feed rate on surface roughness (*Ra*) is not statistically significant. Nevertheless, the optimal surface roughness is achieved with the combination of both the lowest feed rate and cutting time. The surface roughness does not very much with cutting time.

4.4 Regression equations for VB and Ra

The regression equations obtained for the response factors using multiple regressions are as follows:

$$VB = 0.0929 - 3.148\times10^{-4}Vc + 0.0888f - 5.67\times10^{-3}t + 7.9166\times10^{-5}Vc\times t \quad (3)$$

$$Ra = 2.938 - 0.04Vc + 16.239f - 0.0882t + 0.072Vc\times f + 3.474\times10^{-4}Vc\times t + 0.411f\times t + 8.37\times10^{-5}Vc^2 - 109.27f^2 \quad (4)$$

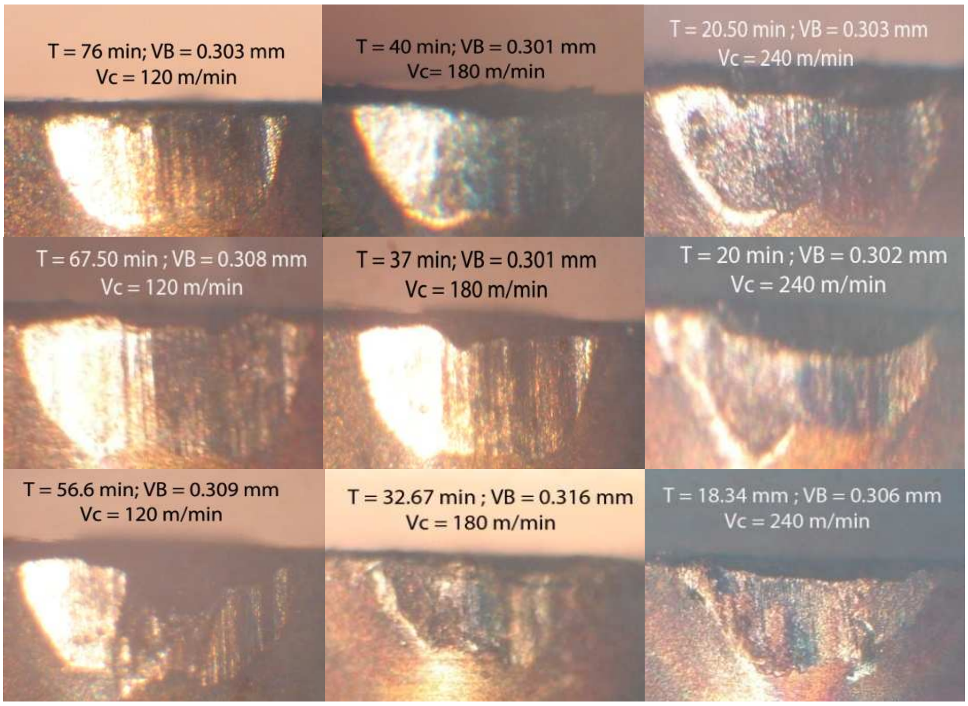

Fig. 4. Micrographs of flank wear for different cutting speeds and feed rates.

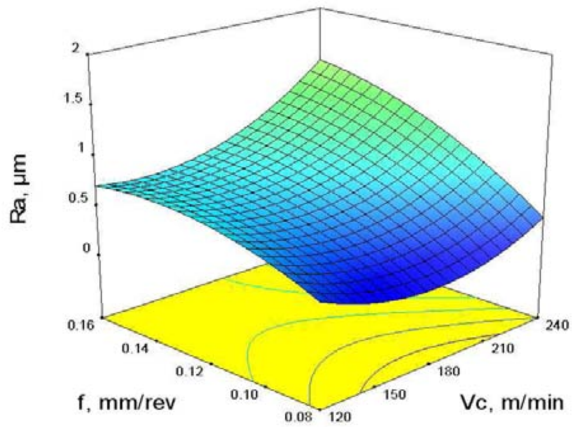

Fig. 5. Effect of feed rate and cutting speed on the *Ra*.

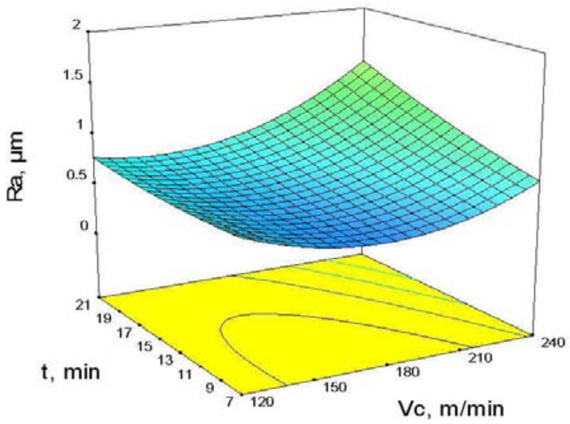

Fig. 6. Effect of cutting time and cutting speed on the *Ra*.

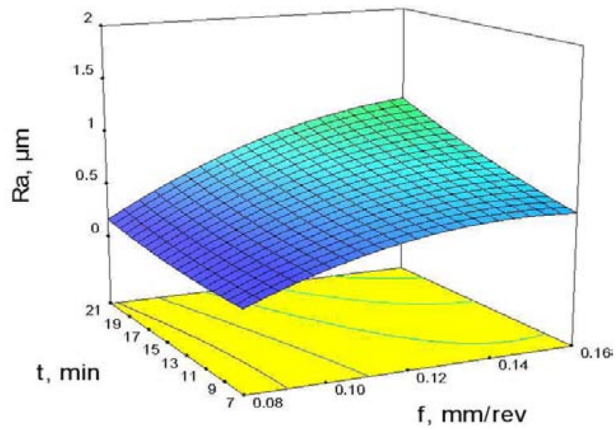

Fig. 7. Effect of cutting time and feed rate on the *Ra*.

The predicted values of response factors flank wear (*VB*) and surface roughness (*Ra*) from regression equations, Eqs. (3) and (4) corresponding to different combinations of machining parameters are reported in Table 4. Moreover, they are compared with the corresponding experimental values illustrated in Figs. 8 and 9. Good agreement is observed between these values as seen in Figs. 10 and 11.

5. Optimization of cutting conditions

The optimal manufacturing conditions for machining hot work steel (AISI H11) with the constraints of cutting parametric range is that corresponding to lower values of both flank wear (*VB*) and surface roughness (*Ra*) during the hard turning process. The constraints used during the optimization process

Table 7. 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
Cutting time, *t*	Is in range	7	21
VB	Minimize	0.066	0.327
Ra	Minimize	0.218	2.24

Table 8. Optimization results.

Solution N°	*Vc*, m/min	*f*, mm/rev	*t*, min	*VB*, mm	*Ra*, µm	Desirability
1	146.507	0.080	7.000	0.095	0.218	0.942
2	147.028	0.080	7.000	0.096	0.218	0.942
3	147.700	0.080	7.000	0.096	0.213	0.941
4	146.475	0.080	7.059	0.096	0.218	0.941
5	147.845	0.081	7.000	0.096	0.218	0.941
6	148.158	0.080	7.000	0.096	0.205	0.941
7	149.065	0.082	7.000	0.096	0.218	0.940
8	150.069	0.082	7.000	0.096	0.218	0.940
9	146.375	0.080	7.227	0.097	0.218	0.939
10	152.388	0.083	7.000	0.097	0.218	0.938
11	153.122	0.084	7.000	0.097	0.218	0.938

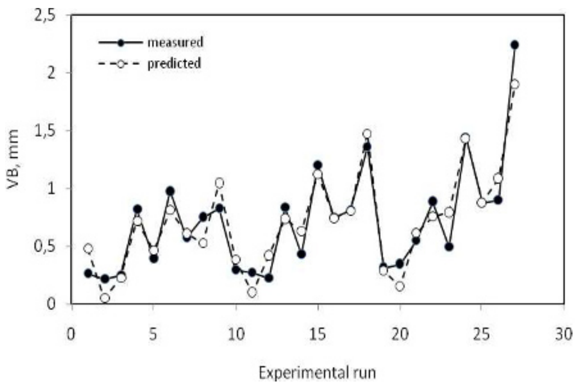

Fig. 8. Comparison of measured and predicted value for flank wear.

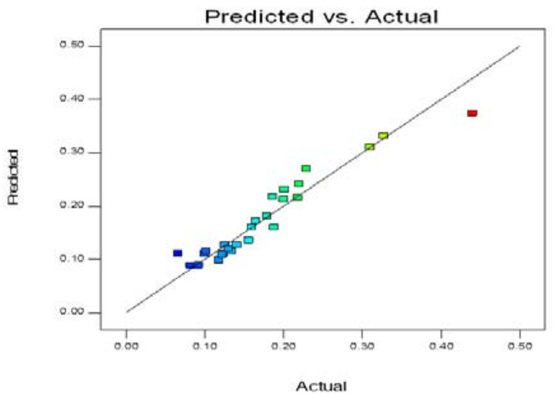

Fig. 10. Comparison between measured and predicted value of *VB*.

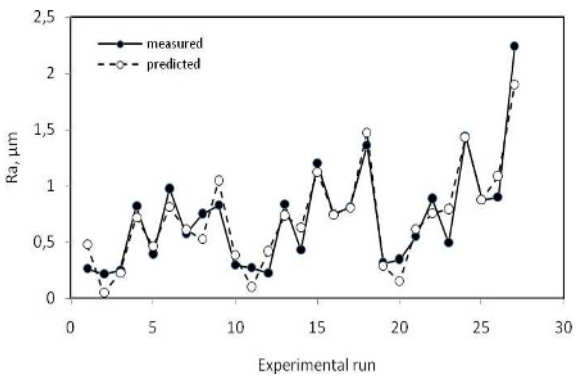

Fig. 9. Comparison of measured and predicted value for *Ra*.

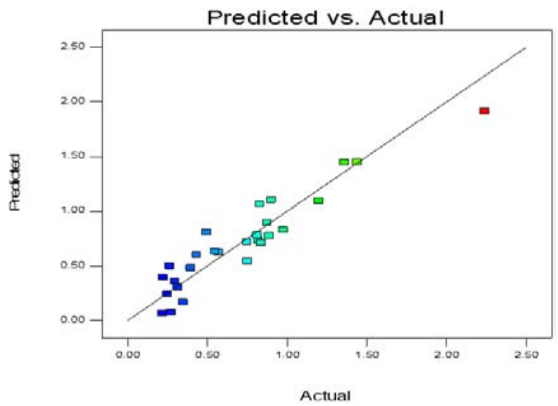

Fig. 11. Comparison between measured and predicted value of *Ra*.

are summarized in Table 7 whereas the optimal solutions are reported in Table 8 in order of decreasing desirability level.

Table 8 shows the RSM optimization results for flank wear (*VB*) and surface roughness (*Ra*). The optimum cutting parameters obtained in Table 8 for cutting speed of (146.51 to 153.12) m/min, feed rate of (0.08 to 0.09) mm/rev and cutting time of (7 to 8) min. The optimized flank wear and surface roughness *Ra* are *VB* = (0.095 to 0.097) mm, (0.205 to 0.218) µm, respectively.

6. Conclusions

In this paper, the application of RSM for the hard turning of AISI H11 steel with CBN tool was presented. Mathematical models of flank wear (*VB*) and the surface roughness (*Ra*) evolutions according to the influence of machining parameters were investigated. Conclusions of this research can be resumed is the following points:

(1) The flank wear of CBN tool increased with cutting speed and feed rate. The present study shows that a higher tool wear rate is noted at cutting speed 240 m/min and feed rate of 0.16 mm/rev.

(2) The flank wear is influenced principally by the cutting time, cutting speed and the interaction effect of cutting speed/cutting time with a contribution of 51.47%, 32.35% and 10.52%, respectively.

(3) The feed rate has a greater influence on the surface roughness (40.32%) followed by cutting speed (11.88%) and cutting time (8.81%).

(4) The statistical models deduced define the degree of influence of each cutting regime element on flank wear and surface roughness. They can also be used for optimization of the hard cutting process.

(5) The ranges of best cutting conditions adopted, are: *Vc* = (146.51 to 153.12) m/min, *f* = (0.08 to 0.09) mm/rev and *t* = (7 to 8) min.

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Nomenclature

ap : Depth of cut, mm
f : Feed rate, mm/rev
HRC : Rockwell hardness
Po : Orthogonal plan
Pf : Working plan
Pr : Reference plan
Ps : Cutting edge plan
Ra : Surface roughness, µm
t : Cutting time, min
VB : Flank wear, mm
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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