

## Surface roughness evaluation of various cutting materials in hard turning of AISI H11

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### ABSTRACT

This paper describes a comparison of surface roughness between ceramics and cubic boron nitride (CBN7020) cutting tools when machining of AISI H11 hot work steels treated at 50 HRC. Plan is designed according to Taguchi's L18 (21×32) orthogonal array. The response surface methodology (RSM) and analysis of variance (ANOVA) were used to check the validity of multiple linear regression models and to determine the effects, contribution, significance and optimal machine settings of process parameters, namely, cutting speed, feed rate and depth of cut on machining parameters on the Ra and Rt. The results of this research work showed that, the feed rate was found to be a dominant factor on the surface roughness, followed by the cutting speed, lastly the depth of cut. The CBN7020 cutting tool showed the better performance than that of ceramic based cutting tool. In addition, the combination of low feed rate and high cutting speed is necessary for minimizing the surface roughness.

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## 1. Introduction

In turning, the machining operation is achieved by using purposely developed cutting tool materials, such as ceramics and cubic boron nitride (CBN). The latter presents a unique property combination between hardness, good resistance at high temperature and thermo-chemical stability. These properties are strongly required in cutting tool materials when machining hard ferrous workpieces. Moreover, the reliability improvement of the ceramics and CBN cutting tools generated the hard turning; a machining process with significant importance in manufacture. Although it is well applied in machining shafts, bearings, pinions, cams and other mechanical components there is a need of research to improve performance of ceramics and CBN tools by taking into account the choice of the machining systems (Bouchelaghem et al., 2010; Fnides et al., 2011).

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In recent years, there are performed various statistical and experimental studies which are based on design and analysis of experiment methods to determine the effects of cutting parameters on the surface roughness occurred in hard/finish turning of various materials. The work of Sahin and Motorcu (2008) presents experimental investigated the surface roughness of AISI 1050 steel that was machined by turning with cubic boron nitride (CBN) and ceramic cutting tools. They determined that the feed rate is the most effective parameter on the average surface roughness ( $Ra$ ) by using response surface methodology (RSM). They obtained a  $0.823 \mu\text{m}$   $Ra$  value with CBN tool when turning a 484 Hardness Vickers (HV) hardness workpiece. Aouici et al. (2012) investigated the effects of cutting speed, feed rate, workpiece hardness and depth of cut on surface roughness and cutting force components in hard turning. AISI H11 steel, hardened to 40, 45 and 50 HRC, respectively, was machined using cubic boron nitride tools. Mathematical models were developed for surface roughness and cutting force components using the response surface methodology (RSM). 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. Thiele and Melkote (1999) carried out an experimental investigation of effects of workpiece hardness and tool edge geometry on surface roughness in finish hard turning using CBN tools. They applied an analysis of variance (ANOVA) to the experimental results in order to distinguish whether differences in surface quality for various runs were statistically important. Horng et al. (2008) presented a model to evaluate the machinability of Hadfield steel by applying RSM and Analysis of Variance (ANOVA) techniques. Kribes et al. (2012) performed statistical analysis to study the influence of cutting speed, feed rate and depth of cut on surface roughness in hard turning of 42CrMo4 steel with coated mixed ceramics inserts.

The aim of the work reported in Asiltürk and Neseli (2011), was to model the surface roughness in turning of AISI 304 austenitic stainless steel under dry conditions, using the Response Surface Methodology (RSM). An orthogonal array was applied to study the influence of cutting parameters (cutting speed, feed rate and depth of cut) on the surface roughness.

Few work have compared the performance of various tool materials during hard turning (Sales et al., 2009; Mahfoudi et al., 2008). While comparing the tool life of ceramics and CBN tools when machining hardened steels, results showed that cutting velocity is predominant factor for tool wear followed by tool hardness. Feed has the least effect on tool wear (Sales et al., 2009). CBN inserts show better performance than the ceramics. When comparing performance of coated cemented carbide, mixed ceramics and PCBN-H tools while turning W320 steel (Mahfoudi et al., 2008), experiments showed that cemented carbides performed better at speeds up to 120 m/min while CBN-(High) tools are superior at high cutting speeds (up to 200 m/min). Mixed ceramics did not perform well. Adhesion, abrasion and plastic deformation were dominant wear mechanisms, although chipping on the rake and flank faces and catastrophic failure were also observed in some experiments. CBN at low speeds are susceptible to high wear promoted due to chipping.

Recently, Elbah et al. (2013) applied response surface methodology (RSM) and ANOVA to compare the machinability of hardened AISI 4140 cold work tool steel wiper and conventional ceramics (CC6050WH and CC6050). The results indicated that surface roughness of 4140 steel was improved as cutting speed was elevated and deteriorated with feed rate. However, the surface quality obtained with the wiper ceramic insert allowed a surface finish as good when compared with conventional ceramic insert is 2.5. Fnides et al. (2013) investigated the productivity in terms of volume chip carved of six cutting tools for two different cutting conditions in straight hard turning of X38CrMoV5-1 (50 HRC). They found that for the first cutting regime ( $V_c = 120 \text{ m/min}$ ,  $ap = 0.15 \text{ mm}$  et  $f = 0.08 \text{ mm/rev}$ ), the productivity of the uncoated cermets CT5015, the coated cermets GC1525, the uncoated carbide H13A, the reinforced ceramic CC670, the coated carbide GC3015 and the mixed ceramic CC650 are (2160; 1440; 6480; 11520; 23040 and 70560)  $\text{mm}^3$ , respectively. The productivity of these three selected tools, i.e. mixed ceramic CC650, reinforced ceramic CC670 and coated carbide GC3015 for the second cutting regime ( $f = 0.08 \text{ mm/rev}$ ,  $ap = 0.15 \text{ mm}$  and  $V_c = 90 \text{ m/min}$ ) are (85860; 12960 and 30780)  $\text{mm}^3$ , respectively. Their results prove that the mixed ceramic  $\text{Al}_2\text{O}_3 + \text{TiC}$  (CC650) is more efficient than other tools used in terms of productivity.

In the work of Davim and Figueira (2007), performed statistical analysis to study the influence of cutting speed and feed rate on flank wear, specific cutting pressure, and surface roughness in hard turning of AISI D2 cold work tool steel with conventional ceramic inserts. Their results prove that the wiper ceramic cutting tool CC650WG has the better performance compared with traditional ceramic cutting tools CC650, in particular the surface roughness of the workpiece. In another studies, Federico et al. (2008) performed turning of hardened steel using TiCN/Al<sub>2</sub>O<sub>3</sub>/TiN coated carbide and PCBN tools, respectively. The results concluded that machining of medium hardened steels was productive with TiCN/Al<sub>2</sub>O<sub>3</sub>/TiN coated carbide tools. Lima et al. (2005) investigated the machinability of hardened steels AISI 4340 and AISI D2 with different of hardness values, using various cutting tool materials. The results indicated that when turning AISI 4340 steel the surface roughness improved with cutting velocity and increases is deteriorated when feed rate increases. Depth of cut presents little effect on the surface roughness values. Gaitonde et al. (2009) revealed that, wiper insert performed better with reference to surface roughness and tool wear, while the conventional insert is useful in reducing the machining force, power and specific cutting force during turning of high chromium AISI D2 cold work tool steel with ceramic inserts. Okada et al. (2011) have investigated cutting performance of CBN tools and PVD-coated carbide tools in end-milling of hardened steel. In this study, the influence of workpiece hardness on surface roughness was summarized.

## 2 Experimental works

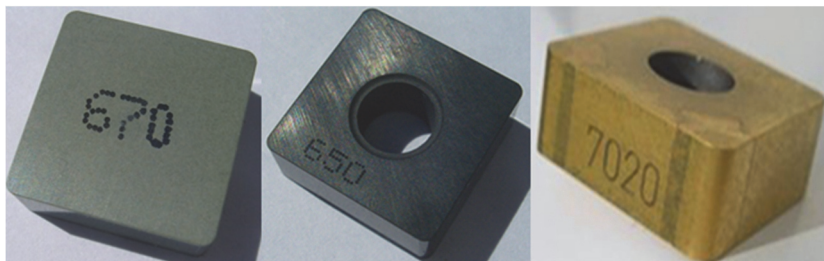
### 2.1. Work piece material, machine and tool

Round bars with 75 mm diameter and 400 mm length were used as work piece materials. The workpiece material was AISI H11, hot work steel which is popularly used in hot form pressing. Its resistance to high temperature and its aptitude for polishing enable it to answer most requests for hot dieing and molding under pressure. Its chemical composition (in wt.%) are given as: C 0.35; Cr 5.26; Mo 1.19; V 0.50; Si 1.01; Mn 0.32; S 0.002; P 0.016; Fe 90.31 and other components 1.042. It is hardened to ~ 50 HRC. Its hardness was measured by a digital durometer DM2D. Turning experiments were performed in dry conditions using a universal lathe type SN 40C with 6.6 kW spindle power. The cutting inserts used are reinforced ceramic CC670, mixed ceramic CC650, and cubic boron nitride CBN7020 (Fig. 1). These inserts are removable, of square form with eight cutting edges. Their characteristics are shown in Table 1.

**Table 1**

Characteristics of used inserts (Çiçek et al. 2013)

Cutting materials	Designation	Chemical composition	Hardness (HV)	Thermal conductivity (Wm <sup>-1</sup> K <sup>-1</sup> )
Reinforced ceramic CC670	SNGN120408 T 010 20	Al <sub>2</sub> O <sub>3</sub> (80%) + SiC (20%)	~ 2000	~ 18
Mixed ceramic CC650	SNGA120408 T 010 20	Al <sub>2</sub> O <sub>3</sub> (70%) + TiC (22.5%)	~ 1800	~ 24
Cubic boron nitride CBN7020	SNGA120408 S 010 20	CBN (57%) + Ti(C, N) (35%)	~ 2800	~ 740



**Fig. 1.** Cutting tools: (a) CC650, (b) CC670 and (c) CBN7020

The toolholders adapted are of designation CSBNR2525M12 and PSBNR2525M12 with geometry of the active part characterized by the following angles:  $\chi = 75^\circ$ ;  $\alpha = 6^\circ$ ;  $\gamma = -6^\circ$ ;  $\lambda = -6^\circ$ .

The test specimens have been hardened to the required hardness of 60HRC through quenching at 940°C and tempering at 280°C. Its hardness was measured by a digital durometer (DM2-D 390). The all surface roughness measurements have been obtained directly on the tool machine and without disassembling the workpiece by means of roughness meter (Surftest 301 Mututoyo). Illustration of measured surface roughness is given in Fig. 2. The length examined was 2.4 mm with a basic span of 3. The measured values of  $Ra$  and  $Rt$  are within the range 0.05–40  $\mu\text{m}$ . This roughness was directly measured on the workpiece, without dismounting from the lathe, in order to reduce uncertainties due to resumption operations. The measurements were repeated three times at three reference lines equally positioned at 120°.

## 2.2. Design of experiments

The aim of the experiments was to analyze the effects of cutting parameters on surface roughness during the hard turning of AISI H11. The experiments were carried out using full factorial method (Taguchi's  $L_{18}$ ), and results were analyzed with RSM. The RSM procedure is capable of determining a relationship between independent input process parameters and output data. This procedure includes 6 steps. These are, (1) defining the independent input variables and the desired output responses, (2) adopting an experimental design plan, (3) performing regression analysis with the multiple linear regression models of RSM, (4) calculating the ANOVA for the independent input variables in order to find parameters which significantly affect the response, (5) determining the situation of multiple linear regression models of RSM and finally, (6) optimizing, conducting confirmation experiment and verifying the predicted performance characteristics (Aouici et al. 2012). The selected cutting parameters were cutting speed, feed rate and depth of cut. Various levels of cutting parameters are given in Table 2. The results obtained from experiments without cutting fluid are presented in Table 3.

In the current study, the relationship between the input, called the cutting conditions (cutting speed ( $Vc$ ), feed rate ( $f$ ) and depth of cut ( $ap$ )) and the output  $Y$  define as a machinability aspect (surface roughness criteria ( $Ra$  and  $Rt$ )) is given as :

$$Y = \varphi(Vc, f, ap), \quad (1)$$

where  $\varphi$  is the response function. The approximation of  $Y$  is proposed by using a multiple linear mathematical model, which is suitable for studying the interaction effects of process parameters on machinability characteristics. In the present work, the RMS based multiple linear mathematical model is given by:

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

where  $a_0$  is the free term of the regression equation, the coefficients  $b_1, b_2, \dots, b_k$  are the linear; while  $b_{12}, b_{13}, \dots, b_{k-1}$  are the interacting terms.  $X_i$  represents input parameters ( $Vc, f$  and  $ap$ ).

**Table 2**

Assignment of the factor levels

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

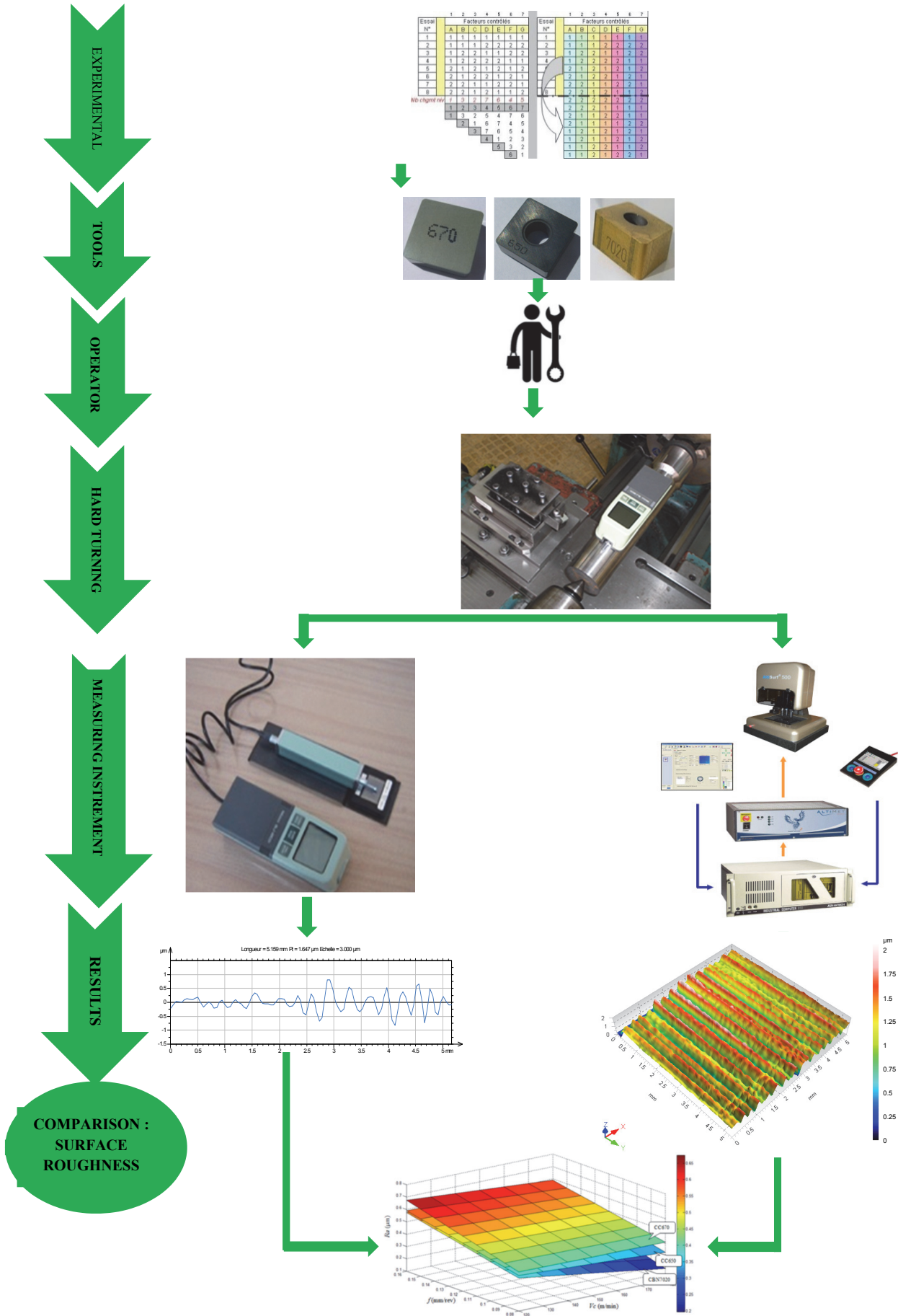


Fig. 2. Illustration of measured surface roughness criteria

### 3. Results and discussion

Experimental matrix and results of surface roughness criteria when hard turning of AISI H11 hot work steel were analyzed for three different cutting tools, namely reinforced ceramic CC670, mixed ceramic CC650, and cubic boron nitride CBN7020; is shown in Table 3. Regression equations for arithmetic mean roughness ( $R_a$ ) and total roughness ( $R_t$ ) were developed based on experimental data. The values of the coefficients involved in the equation were calculated by regression method by using the Design Expert software. Equations developed for surface roughness criteria for different cutting tools are given below:

**Table 3**

$L_{18}(2^1 \times 3^2)$  orthogonal array and experimental data

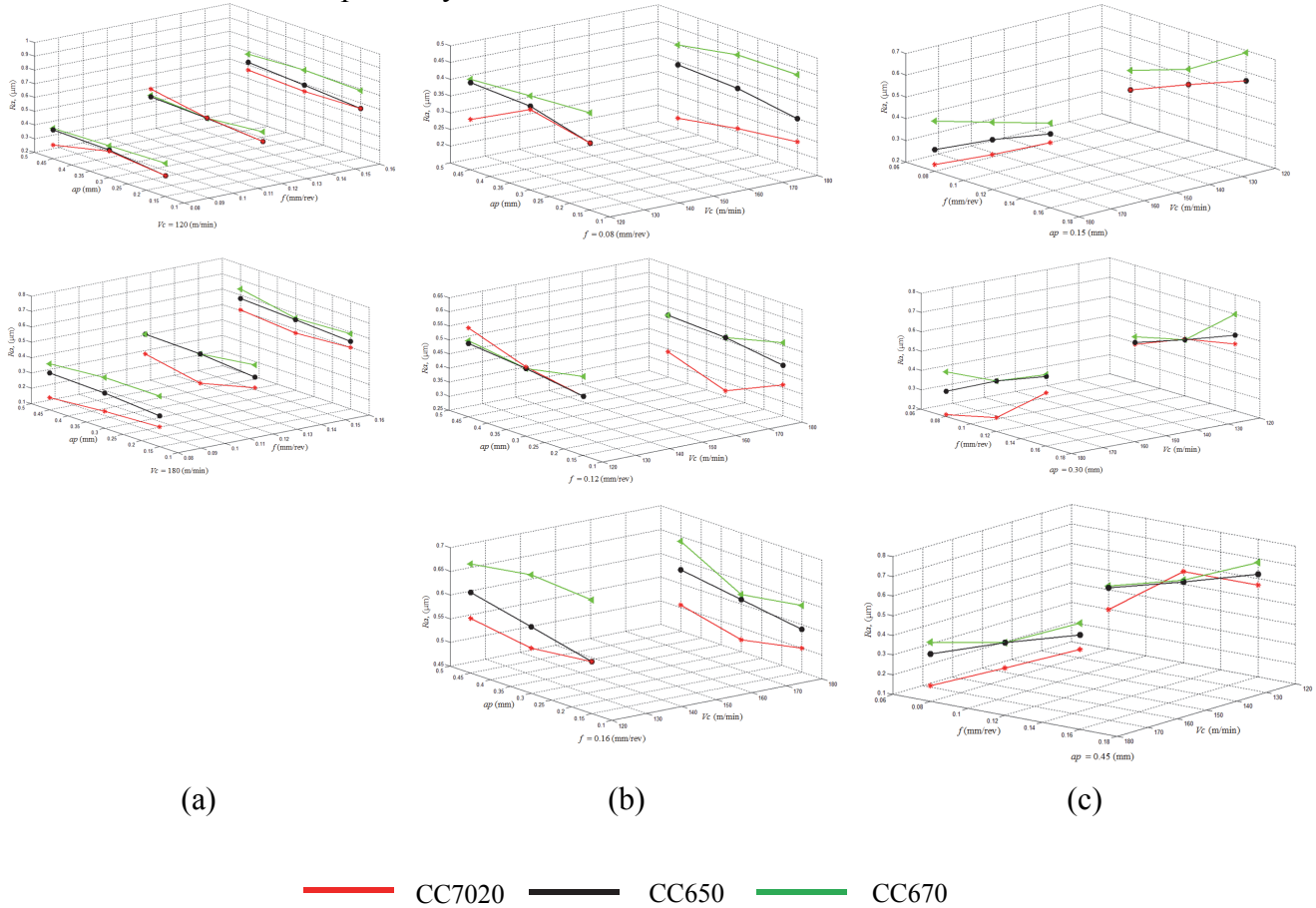
Test N°	Machining parameters			Response factors					
	$V_c$ (m/min)	$f$ (mm/rev)	$ap$ (mm)	CC670		CC650		CBN7020	
				$R_a$ ( $\mu\text{m}$ )	$R_t$ ( $\mu\text{m}$ )	$R_a$ ( $\mu\text{m}$ )	$R_t$ ( $\mu\text{m}$ )	$R_a$ ( $\mu\text{m}$ )	$R_t$ ( $\mu\text{m}$ )
1	120	0.08	0.15	0.440	2.70	0.350	3.32	0.350	2.00
2	120	0.08	0.30	0.430	2.79	0.400	2.67	0.390	2.30
3	120	0.08	0.45	0.420	2.81	0.410	3.07	0.300	1.80
4	120	0.12	0.15	0.530	3.22	0.460	3.54	0.460	3.00
5	120	0.12	0.30	0.490	3.30	0.490	3.59	0.495	2.85
6	120	0.12	0.45	0.520	3.41	0.510	3.60	0.565	3.05
7	120	0.16	0.15	0.690	4.79	0.560	3.75	0.560	3.70
8	120	0.16	0.30	0.700	4.82	0.590	3.97	0.545	4.15
9	120	0.16	0.45	0.680	4.90	0.620	4.16	0.565	3.05
10	180	0.08	0.15	0.430	2.69	0.300	2.80	0.230	1.60
11	180	0.08	0.30	0.430	2.75	0.330	2.82	0.210	1.50
12	180	0.08	0.45	0.400	2.83	0.340	2.85	0.180	1.20
13	180	0.12	0.15	0.510	3.18	0.430	3.36	0.360	2.20
14	180	0.12	0.30	0.460	3.25	0.460	3.40	0.270	1.70
15	180	0.12	0.45	0.470	3.33	0.470	3.41	0.340	2.20
16	180	0.16	0.15	0.590	4.43	0.540	3.67	0.500	3.20
17	180	0.16	0.30	0.570	4.56	0.560	3.76	0.475	2.35
18	180	0.16	0.45	0.640	4.74	0.580	3.81	0.505	2.85

#### 3.1. Effect of cutting parameters on arithmetic mean roughness ( $R_a$ )

Surface roughness measurement is one of the most important requirements in many engineering applications, as it is considered an important index of product quality. In the turning operations, the surface roughness is mainly controlled by the cutting conditions. Fig. 3 depicts the interaction effects of depth of cut–feed rate, depth of cut–cutting speed and feed rate–cutting speed on arithmetic mean roughness during hard turning of hot work steel using three different cutting tools at two levels of cutting speed and three levels of feed rate and depth of cut, respectively. According to the Fig. 3a, it can be seen that  $R_a$  increases with feed rate and better with cutting speed at  $V_c = 180$  m/min. The evolution of  $R_a$  with depth of cut shows that this parameter has a very weak effect compared to that of the feed rate. This is due to the increased length of contact between the tool and the workpiece. This improves the conditions of heat flow from the cutting zone and consequently slows down the process wear (Aouici et al., 2014).

As seen from Fig. 3b that  $R_a$  value increases when the feed rate is increased from 0.08 mm/rev to 0.16 mm/rev. This result shows that the need to choose lower feed rate is revealed to obtain small values of  $R_a$  during machining of hard materials such as AISI H11, particularly. It can be seen from Fig. 3c that  $R_a$  value increases linearly as the feed rate is increased from 0.08 mm/rev to 0.16 mm/rev when machining of AISI H11 with 50 HRC. On the other hand, it was determined that the  $R_a$  values obtained by the CBN7020 cutting tool at all cutting conditions, except 120 m/min cutting speed, 0.12 mm/rev feed rate and 0.45 mm depth of cut are lower. In general the CBN7020 tool produces a better surface finish

compared with CC650 and CC670 inserts when machining of AISI H11 with 50 HRC. Table 4 shows the results of analysis of variance (ANOVA) for arithmetic mean roughness of CC670, CC650 and CBN7020 tools. 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 (SCsq.), mean square (MS), F-values and probabilities (P-value), in addition to the contribution (Cont. %) of each factor, are also shown. From Table 4, it can be seen that the feed rate (Cont.  $\approx 90.62$ ; Cont.  $\approx 90.01$  and Cont.  $\approx 69.28$ ) % followed by cutting speed (Cont.  $\approx 5.55$ ; Cont.  $\approx 4.97$  and Cont.  $\approx 28.00$ ) % had the greatest influence on tools CC670, CC650 and CBN7020, respectively. The depth of cut (Cont.  $\approx 0.19$  and Cont.  $\approx 0.01$ ) % does not present a statistically significant effect on arithmetic mean roughness for reinforced ceramic CC670 and cubic boron nitride CBN7020 respectively.



**Fig. 3.** Effect of cutting conditions on arithmetic mean roughness for (CC670, CC650 and CBN7020)

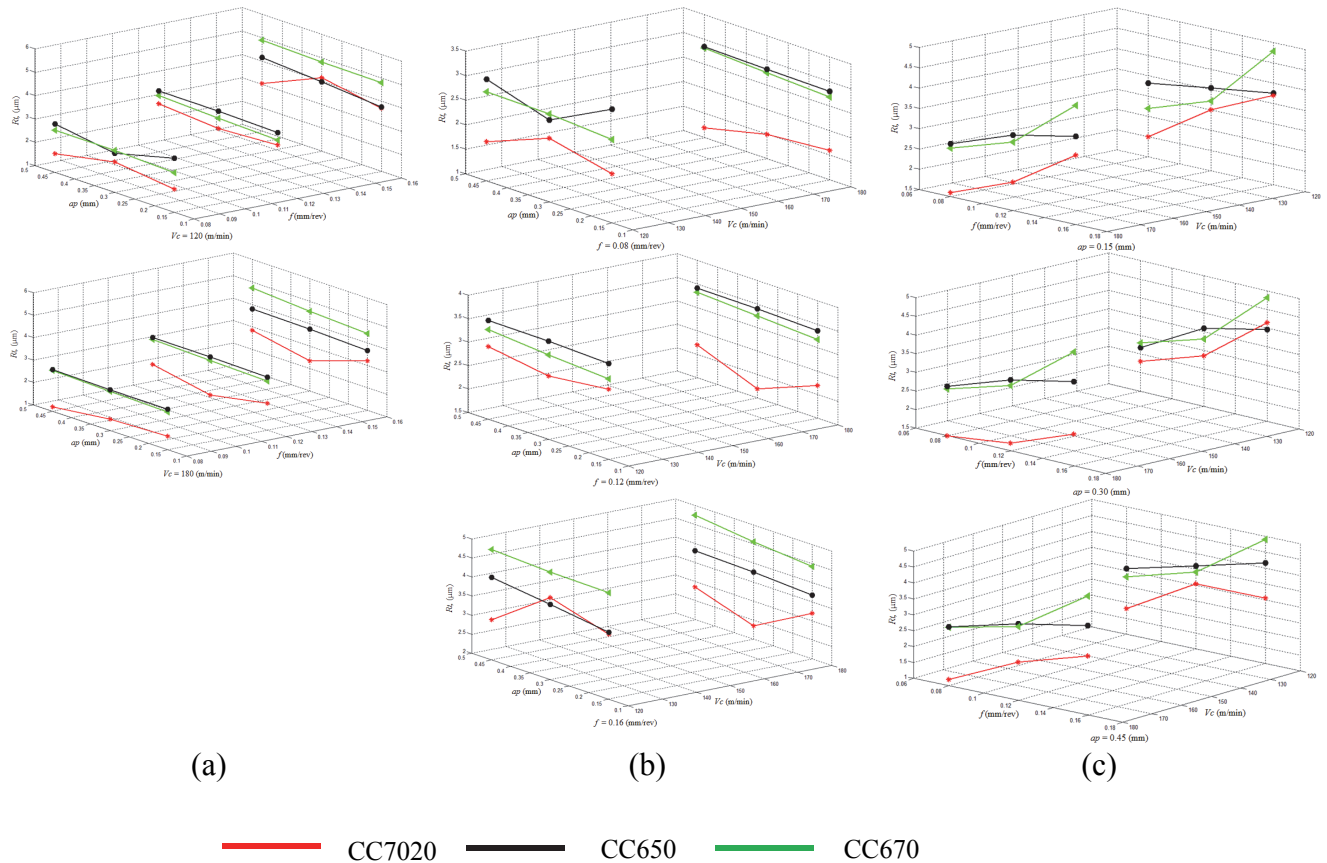
### 3.2. Effect of cutting parameters on total roughness ( $R_t$ )

Fig. 4 shows the interaction effects of depth of cut–feed rate, depth of cut–cutting speed and feed rate–cutting speed on total roughness during hard turning of hot work steel using three different cutting tools namely, reinforced ceramic CC670, mixed ceramic CC650 and cubic boron nitride CBN7020; at two levels of cutting speed and three levels of feed rate and depth of cut, respectively.

Fig. 4a shows the variation of the total roughness versus the depth of cut and feed rate at two levels of cutting speed.  $R_t$  values increase when the feed rate increases for third cutting tool materials, because its increase generates helicoid furrows, the result of tool shape and helicoid movement tool-workpiece. These furrows are deeper and broader as the feed rate increases. However, a qualitative comparison can be made; for example, Elbah et al. (2013) found that the feed rate is the important factor affecting surface roughness. For this reason, weak feed rate have to be employed during turning operation. As can be seen clearly in Fig. 2a, there is a regular interaction between the factors and the total roughness. From Fig. 4b

illustrates the evolution of the total roughness according to the depth of cut and cutting speed at three levels of feed rate; 0.08, 0.12 and 0.16 mm/rev, it can be observed that, total roughness is lowly sensitive with to depth of cut at the all values of feed rate or cutting speed. Similar results were reported by Azizi et al. (2012) during hard turning of AISI 52100 steel with ceramic tool. From Figure 4c illustrates the evolution of the specific cutting force according to the depth of cut and feed rate, specific cutting force decreases with increase in depth of cut and feed rate. The variation of feed rate with cutting speed at three levels of depth of cut on total roughness is presented in Fig. 4c. The comparison reveals that, in case of CC670 reinforced ceramic insert, the total roughness is highly sensitive to feed rate as compared to CC650 and CBN720. In general, it can be concluded that the feed rate exhibits maximum influence on total roughness as compared to depth of cut and cutting speed.

Table 5 presents ANOVA results for  $R_t$ . It can be seen that the feed rate is the most important factor affecting surface finish  $R_t$ . Its contribution is (98.34; 90.63 and 68.31) % respectively; (CC670, CC650 and CBN7020) to these models. The second factor influencing  $R_t$  is cutting speed. Its contribution is (6.28 and 28.98) % respectively (CC650 and CBN7020). The effect of the depth of cut is not significant because its contribution is (0.74; 0.63 and 2.07) % respectively; (CC670, CC650 and CBN7020) to these models.



**Fig. 4.** Effect of cutting conditions on total roughness for (CC670, CC650 and CBN7020)



**Table 4**  
Analysis of variance for surface roughness  $R_a$

Source	SS	DF	MS	F-value	Prob.	Cont. %
<b>CC670 insert</b>						
Model	0.16023472	6	0.02670579	27.51526387	< 0.0001	
$V_c$	0.00888889	1	0.00888889	9.15831924	0.0115	5.55
$f$	0.1452	1	0.1452	149.6011448	< 0.0001	90.62
$ap$	0.0003	1	0.0003	0.309093274	0.5894	0.19
$V_c \times f$	0.0048	1	0.0048	4.945492390	0.0480	3.00
$V_c \times ap$	3.3333E-05	1	3.3333E-05	0.034343697	0.8564	0.02
$f \times ap$	0.0010125	1	0.0010125	1.043189801	0.3290	0.63
Residual	0.01067639	11	0.00097058			
Total	0.17091111	17				100
SD = 0.0312				$R^2 = 0.9375$		
Mean = 0.5222				$R^2$ Adjusted = 0.9035		
Coefficient of variation = 5.9657				$R^2$ Predicted = 0.8386		
Predicted residual error of sum of squares (PRESS) = 0.0276				Adequate precision = 14.598		
<b>CC650 insert</b>						
Model	0.161272222	6	0.026878704	406.2582697	< 0.0001	
$V_c$	0.008022222	1	0.008022222	121.2519084	< 0.0001	4.97
$f$	0.1452	1	0.1452	2194.625954	< 0.0001	90.01
$ap$	0.007008333	1	0.007008333	105.9274809	< 0.0001	4.34
$V_c \times f$	0.000833333	1	0.000833333	12.59541985	0.0046	0.52
$V_c \times ap$	0.000208333	1	0.000208333	3.148854962	0.1036	0.13
$f \times ap$	0.00005	1	0.00005	0.755732	1.0000	0.03
Residual	0.000727778	11	6.61616E-05			
Total	0.162	17				100
SD = 0.008				$R^2 = 0.9955$		
Mean = 0.467				$R^2$ Adjusted = 0.9931		
Coefficient of variation = 1.743				$R^2$ Predicted = 0.9875		
Predicted residual error of sum of squares (PRESS) = 0.002				Adequate precision = 61.2243		
<b>CBN7020 insert</b>						
Model	0.266988889	6	0.044498148	23.41385419	< 0.0001	
$V_c$	0.074755556	1	0.074755556	39.33457348	< 0.0001	28.00
$f$	0.185008333	1	0.185008333	97.34693064	< 0.0001	69.28
$ap$	2.08333E-06	1	2.08333E-06	0.0010962	0.9742	0.01
$V_c \times f$	0.004408333	1	0.004408333	2.319558863	0.1560	1.65
$V_c \times ap$	0.001302083	1	0.001302083	0.6851249	0.4254	0.49
$f \times ap$	0.0015125	1	0.0015125	0.795841084	0.3914	0.57
Residual	0.020905556	11	0.001900505			
Total	0.287894444	17				100
SD = 0.0436				$R^2 = 0.9274$		
Mean = 0.4056				$R^2$ Adjusted = 0.8878		
Coefficient of variation = 10.7494				$R^2$ Predicted = 0.8003		
Predicted residual error of sum of squares (PRESS) = 0.0575				Adequate precision = 15.6534		

### 3.3. Correlations

The correlation between the cutting factors and measured surface roughness criteria ( $R_a$  and  $R_t$ ) are determined from the following multiple linear regression equations (Eqs. (4–8) for three different cutting tools, namely reinforced ceramic CC670, mixed ceramic CC650, and cubic boron nitride CBN7020. The coefficients of determination ( $R^2$ ) values of developed machinability models have very good correlations between the experimental and predicted values of machinability characteristics. The arithmetic mean roughness for ( $R_{aCC670}$ ,  $R_{aCC650}$  and  $R_{aCBN7020}$ ) models are given below in Eqs. (3-5). Their coefficients of determination ( $R^2$ ) are 93.75; 99.55 and 92.74%.

**Table 5**  
Analysis of variance for surface roughness  $R_t$

Source	SS	DF	MS	F-value	Prob	Cont %
<b>CC670 insert</b>						
Model	11.54	6	1.92	25.35	< 0.0001	
$V_c$	0.053	1	0.053	0.70	0.4196	0.46
$f$	11.35	1	11.35	149.57	< 0.0001	98.34
$ap$	0.085	1	0.085	1.12	0.3125	0.74
$V_c \times f$	0.047	1	0.047	0.62	0.4485	0.41
$V_c \times ap$	3.008E-003	1	3.008E-003	0.040	0.8458	0.03
$f \times ap$	3.612E-003	1	3.612E-003	0.048	0.8313	0.03
Residual	0.83	11	0.076			
Total	12.38	17				100
SD = 0.28				$R^2 = 0.9326$		
Mean = 3.58				$R^2$ Adjusted = 0.8958		
Coefficient of variation = 7.69				$R^2$ Predicted = 0.8265		
Predicted residual error of sum of squares (PRESS) = 2.15				Adequate precision = 12.936		
<b>CC650 insert</b>						
Model	2.87	6	0.48	20.00	< 0.0001	
$V_c$	0.18	1	0.18	7.44	0.0196	6.28
$f$	2.60	1	2.60	108.87	< 0.0001	90.63
$ap$	0.018	1	0.018	0.74	0.4089	0.63
$V_c \times f$	2.083E-004	1	2.083E-004	8.710E-003	0.9273	0.02
$V_c \times ap$	3.333E-005	1	3.333E-005	1.394E-003	0.9709	0.01
$f \times ap$	0.070	1	0.070	2.94	0.1144	2.44
Residual	0.26	11	0.024			
Total	3.13	17				100
SD = 0.15				$R^2 = 0.9160$		
Mean = 3.42				$R^2$ Adjusted = 0.8702		
Coefficient of variation = 4.52				$R^2$ Predicted = 0.7398		
Predicted residual error of sum of squares (PRESS) = 0.82				Adequate precision = 13.632		
<b>CBN7020 insert</b>						
Model	9.66	6	1.61	14.67	0.0001	
$V_c$	2.80	1	2.80	25.52	0.0004	28.98
$F$	6.60	1	6.60	60.14	< 0.0001	68.31
$Ap$	0.20	1	0.20	1.82	0.2040	2.07
$V_c \times f$	0.041	1	0.041	0.37	0.5543	0.42
$V_c \times ap$	2.083E-004	1	2.083E-004	1.898E-003	0.9660	0.01
$f \times ap$	0.020	1	0.020	0.18	0.6777	0.21
Residual	1.21	11	0.11			
Total	10.87	17				100
SD = 0.33				$R^2 = 0.8889$		
Mean = 2.48				$R^2$ Adjusted = 0.8283		
Coefficient of variation = 13.34				$R^2$ Predicted = 0.6534		
Predicted residual error of sum of squares (PRESS) = 3.77				Adequate precision = 12.248		

$$Ra_{CC670} = 0.0975 + 0.00115V_c + 4.6875f - 0.31388ap - 0.01667V_c \times f + 0.00037V_c \times ap + 1.875f \times ap, \quad (3)$$

$$Ra_{CC650} = 0.27722 - 0.001259V_c + 1.70833f + 0.3ap + 0.00694V_c \times f - 0.00092V_c \times ap + 2.6577 \times 10^{-15} f \times ap, \quad (4)$$

$$Ra_{CBN7020} = 0.62194 - 0.00337V_c + 0.02083f + 0.06944ap + 0.01597V_c \times f - 0.002315V_c \times ap + 2.2916f \times ap. \quad (5)$$

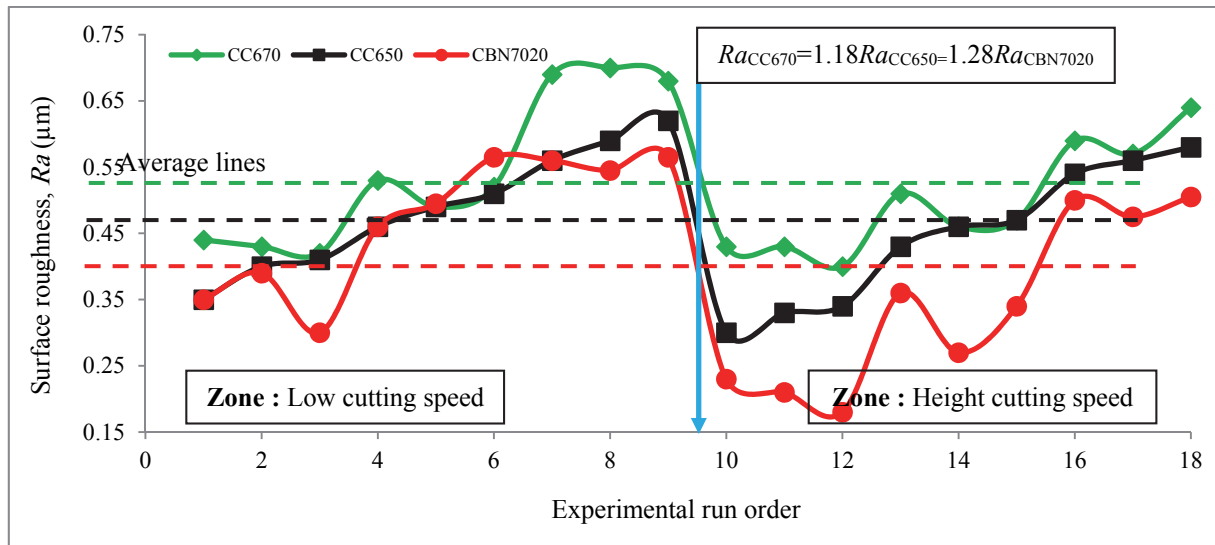
The total roughness model for ( $R_{aCC670}$ ,  $R_{aCC650}$  and  $R_{aCBN7020}$ ) models are given below in Eqs. (6-8). Their coefficients of determination ( $R^2$ ) are 93.26; 91.60 and 88.89%.

$$Rt_{CC670} = 0.11806 + 3.3796 \times 10^{-3} V_c + 31.0625f - 0.39167ap - 0.0521V_c \times f + 3.5185 \times 10^{-3} V_c \times ap + 3.5416f \times ap, \quad (6)$$

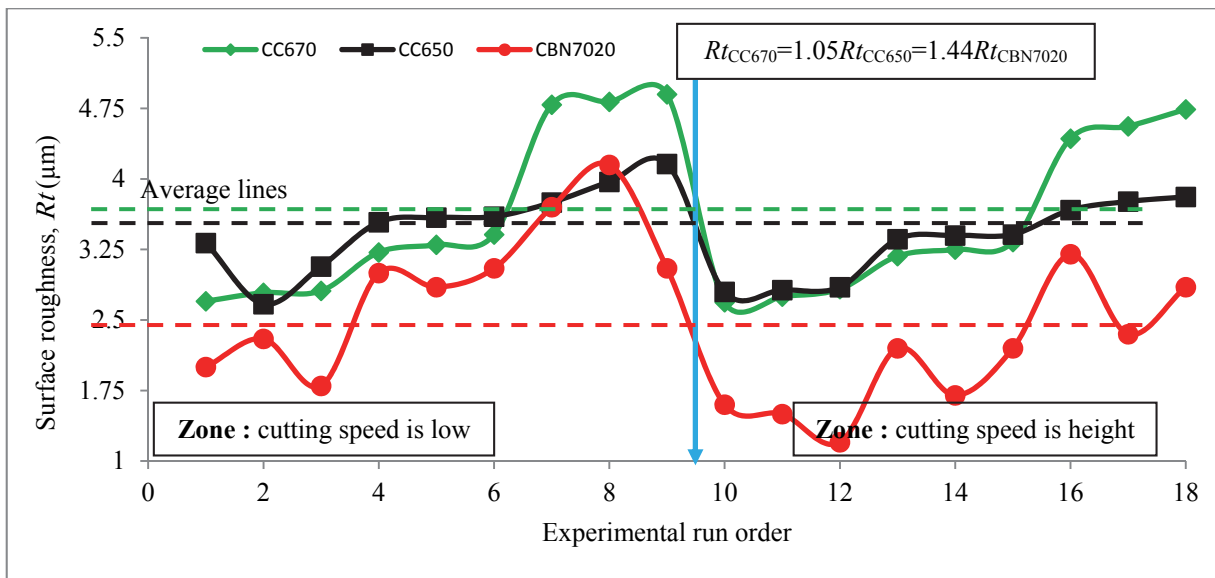
$$Rt_{CC650} = 2.9592 - 3.009 \times 10^{-3} V_c + 7.4792f - 1.675ap - 3.4722V_c \times f + 3.7037 \times 10^{-4} V_c \times ap + 15.625f \times ap, \quad (7)$$

$$Rt_{CBN7020} = 1.3555 - 7.5925 \times 10^{-3} V_c + 28.3333f - 2.4873 \times 10^{-14} ap - 0.0486V_c \times f + 9.2592 \times 10^{-4} V_c \times ap - 8.3333f \times ap. \quad (8)$$

Figs. 5–6 show the comparison between the values of the surface roughness criteria ( $Ra$  and  $Rt$ ) for third cutting tools CC670, CC650 and CBN7020. The insert CBN7020 provides lower values than the both ceramic tools, which translates to a decreased surface roughness with cubic boron nitride CBN7020, because the higher thermal conductivity of CBN tool compared to ceramic tool. For example;  $Ra_{CC670}=1.18Ra_{CC650}=1.28Ra_{CBN7020}$  and  $Rt_{CC670}=1.05Rt_{CC650}=1.44Rt_{CBN7020}$ .



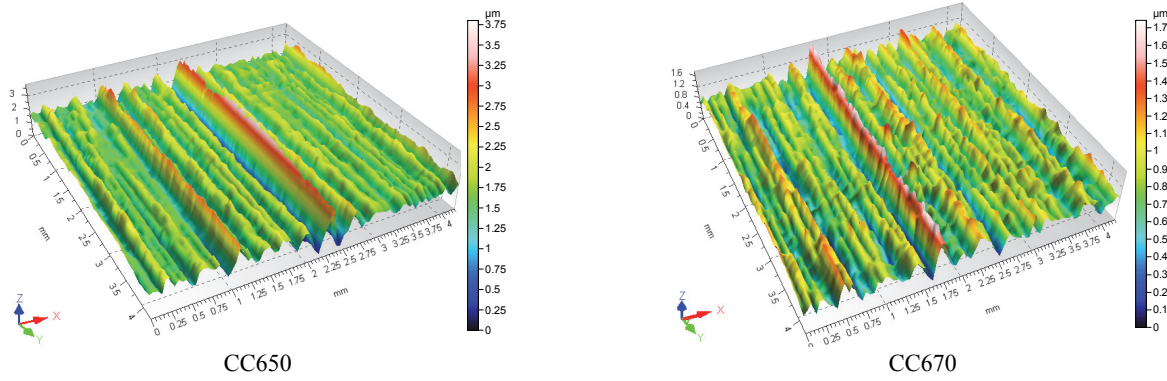
**Fig. 5.** Comparison between CC670, CC650 and CBN7020 for surface roughness  $Ra$



**Fig. 6.** Comparison between CC670, CC650 and CBN7020 for surface roughness  $Rt$

### 3.4. 3D surface topography

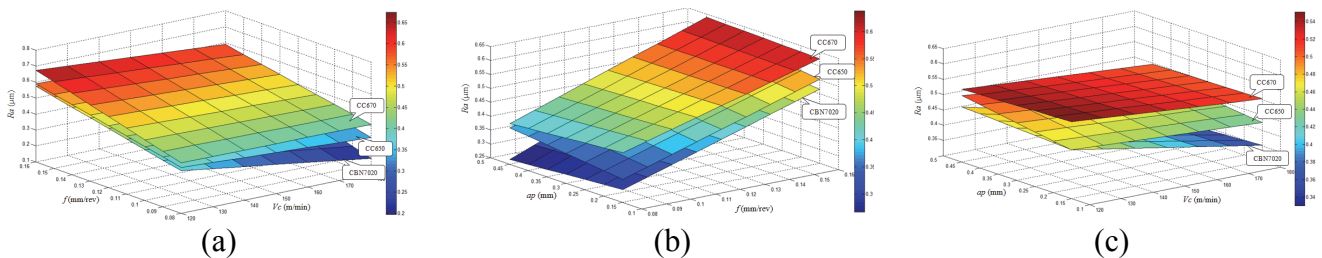
The representative examples of 3D images of hard turned surfaces are visualized by means of four isometric views. The 3D topographies of the as machined surfaces are shown in Fig. 7. The turned surface topography in Fig. 7 show well-defined peaks and valleys. This is mainly because the process turning uses a single cutting edge with defined geometry to generate helicoid furrow the result of tool shape and helicoids movement tool–workpiece.



**Fig. 7.** 3D surface topography

**3.5. Effect of machining parameters on surface response factors**

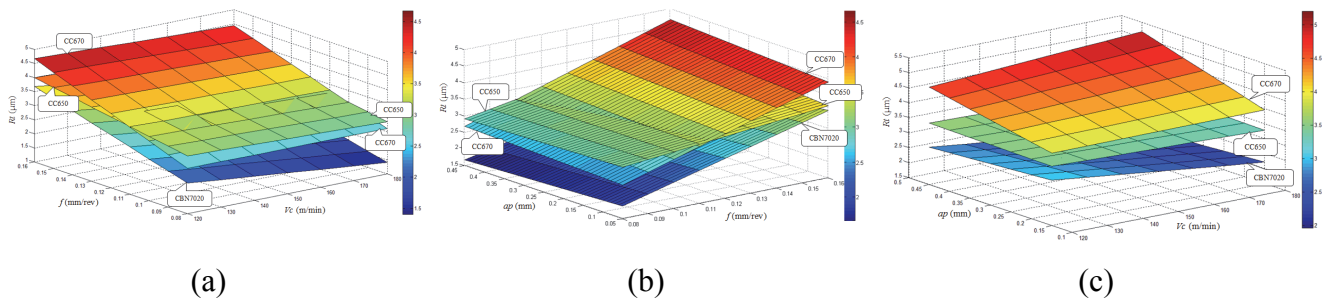
In order to investigate the influences of machining parameters on the surface roughness criteria ( $Ra$  and  $Rt$ ), 3D surface graphs are drawn in Figs. 7 and 8. Firstly, Fig. 7 shows the interaction effects of feed rate ( $f$ ) – cutting speed ( $Vc$ ), depth of cut ( $ap$ ) – feed rate ( $f$ ) and depth of cut ( $ap$ ) – cutting speed ( $Vc$ ) on arithmetic mean roughness ( $Ra$ ) during hard turning of hot work steel using three different cutting tools namely, reinforced ceramic CC670, mixed ceramic CC650 and cubic boron nitride CBN7020. It can be observed from Figs. 7a and b that, for the given cutting speed or depth of cut, the arithmetic mean roughness sharply increases with the increase in feed rate. Fig. 7c shows the estimated response surface for arithmetic mean roughness in relation to depth of cut and cutting speed, while the feed rate is kept at the middle level. As it can be deduced from this figure, the surface roughness ( $Ra$ ) is not statistically significant (Table 5). In general, from the above discussion, Fig. 7 clearly suggests that the surface roughness  $Ra$  can be minimized by employing lower values of feed rate and higher cutting speed, but the depth of cut has a very weak effect compared to that of the feed rate and cutting speed for all cutting tools. In conclusion, the CBN7020 tool produces a better surface finish than the ceramic cutting tools (CC650 and CC670).



**Fig. 7.** Effect of cutting parameters on surface roughness  $Ra$  (CC670, CC650 and CBN7020)

Finally, Fig. 8a presents the interaction between feed rate and cutting speed while the depth of cut is kept at the middle level. Initially, the total roughness increased by increasing the feed rate. The surface roughness  $Rt$  is found to be minimal at high cutting speed with low feed rate. This can be explained that with increasing feed rate, leading to vibration and generating more heat and therefore contributing to a higher surface roughness. However, the surface roughness  $Rt$  decreases sharply with the increase in cutting speed for a given value of feed rate. A comparison study reveals that, the performance of CBN7020 insert is better as compared to both CC650 and CC670 ceramic inserts with reference to surface roughness  $Rt$ . Fig. 8b shows the interaction effect between the depth of cut and the feed rate on the total roughness  $Rt$ . From the illustration, it is seen that surface roughness  $Rt$  increases with an increase in the feed rate. The surface roughness is found to be minimal at all values the depth of cut with low feed rate. Fig. 8c shows the interaction effect between the depth of cut and the cutting speed on the total roughness. From the illustration, it is seen that the total roughness decreases with an increase in the cutting speed, whereas the best surface roughness is observed at a low level of the depth of cut and a high level of the cutting speed. This is due to the fact that, as cutting speed increases, the temperature increases

at the cutting zone that leads to the softening of material and thus reduces the surface roughness (Suresh et al. 2012). In general, the cubic boron nitride CBN7020 has the better performance compared with ceramic cutting inserts (CC6050 and CC670) for all interaction effects between cutting parameters. This is partly explained by the higher thermal conductivity of CBN tool compared to ceramic tool.



**Fig. 8.** Effect of cutting parameters on surface roughness  $R_t$  (CC670, CC650 and CBN7020)

#### 4. Conclusions

In the present paper, an investigative study on machinability aspects of arithmetic mean roughness ( $R_a$ ) and total roughness ( $R_t$ ) has been carried out during hard turning of AISI H11 hot work steel with three different cutting tools, namely reinforced ceramic CC670, mixed ceramic CC650, and cubic boron nitride CBN7020. The response surface methodology (RSM) based mathematical models were developed to analyze the effects of cutting speed, feed rate and depth of cut on machinability. The experiments were planned according to Taguchi's  $L_{18}$  factorial design and the adequacy of the models was tested through analysis of variance (ANOVA). Based on the experimental results and parametric analysis, the following conclusions are drawn.

1. The result of ANOVA proved that the multiple linear regression models allow prediction of surface roughness parameter with a 95% confident interval.
2. The surface roughness criteria ( $R_a$  and  $R_t$ ) are highly sensitive to feed rate in case of hard turning with CC650 and CC670 ceramic inserts as compared to CBN7020 insert. The surface roughness criteria ( $R_a$  and  $R_t$ ) increases with increase in cutting speed in case of CC650 and CBN7020 inserts machining, while the surface roughness criteria increases at 180 m/min cutting speed in case of CC670 machining. On the other hand, the surface roughness is minimal at lower value of feed rate and higher value of cutting speed for all cutting tools.
3. In general, cubic boron nitride CBN7020 has the better performance compared with ceramic cutting inserts (CC6050 and CC670), in particular the surface roughness of the workpiece. Ratios mean value for surface roughness criteria  $R_{aCC670}=1.18R_{aCC650}=1.28R_{aCBN7020}$  and  $R_{tCC670}=1.05R_{tCC650}=1.44R_{tCBN7020}$ .

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