Investigation and Modelling of Surface Roughness in Hard Turning of Sintered Tungsten Carbide (WC 25wt% Co) Using CBN Tool

Minh Tuan Ngo and Quoc Tuan Nguyen
Faculty of Mechanical Engineering, Thai Nguyen University of Technology, 3/2 street, Tich Luong ward, Thai Nguyen City, Vietnam
Email: minhtuanngo@tnut.edu.vn, tuannq@tnu.edu.vn

Abstract— **Sintered Tungsten Carbides with 25wt% Co are commonly applied for the die and molds of the metal forming process because of their high hardness and wear resistance compared with alloy steel. Cubic Boron Nitride (CBN) is a cutting tool material effectively used to machine the dies and molds made from the sintered tungsten carbide 25wt%. Also, the surface roughness is a fundamental parameter for determining the accuracy and quality of dies and molds. In this study, Face Central Composition Design (FCCD) was selected to investigate the influences of the machining parameters on surface roughness Ra and optimize the cutting conditions. The results showed that feed rate was the strongest factor affecting surface roughness. The model for surface roughness based on the cutting parameters (depth, cutting speed, and feed rate) is formulated. Moreover, surface roughness reaches the minimum value of 0.08 µm at the cutting speed of 55 m/min, feed rate of 0.1 mm/rev, and cutting depth of 0.19 mm.**

Index Terms—**tungsten carbide, CBN, hard turning, surface roughness, FCCD, optimization**

I. Introduction

In recent years, super-hard material (as sintered tungsten carbide) is widely applied for the dies and molds of metal forming process or cutting tools because of their prominent features such as having a high toughness, high hardness, and wear resistance. The sintered Tungsten Carbide is made by composing of Tungsten Carbide powders and Cobalt as the binder. The mechanical properties of sintered tungsten carbides depend on the content of Cobalt commonly selected from 2wt% to 25wt% (Saito et al., 2006) [1]. The hardness of sintered tungsten carbides increases, but their toughness reduces by reducing the content of Cobalt. Hence, sintered tungsten carbides with the content of Cobalt less than 10wt% are commonly used to make cutting tools. Besides, the WC rolling shafts or dies usually use the Cobalt content from 20wt% to 25wt% (Lechert, 1987) [2]. Otherwise, the conventional cutting processes faces the challenge to cut sintered tungsten carbide, so many researchers are investigating the EDM, grinding, or polishing process. However, they have many disadvantages like high cost, low productivity, and low machining efficiency (Jahan et al., 2009; Yin et al., 2004) [3][4]. Moreover, other authors are studying some cutting methods including hard milling and turning for machining sintered tungsten carbide to increase the productivity and efficiency.

Surface quality strongly affects the functional performance of machined parts such as wear resistance, tribological properties, and fatigue strength. The surface roughness is one of the important behavior to evaluate the surface qualities (Hosseini et al., 2015) [5]. Kim et al. (2012) studied the turning characteristics of tungsten carbide by using diamond tool with a chamfered diamond edge [6]. The results showed that the surface roughness was better than that of using the conventional tool. The research of Coppini et al. (2013) indicated that the surface roughness doesn't depend on the cutting speed and increases with increasing feed rate [7]. However, this study only investigates with a lower cutting speed from 10 m/min to 30 m/min and uses the full factorial design with two levels. Coppini et al. (2018) concluded that the achieved surface roughness in the turning sintered tungsten carbide using PCD tools similar to those in the grinding process [8]. The effects of cutting parameters on surface roughness in turning process of WC-Co material by using PCD tools were studied (Zębala et al., 2015; Zębala & Kowalczyk, 2014; Zębala & Kowalczyk, 2015) [9][10][11]. Tsurimoto et al. (2012) only compared the tool wear, surface roughness, and chip formation in turning of tungsten carbide with different cobalt content [12]. The results indicated that the CBN tool is suitable for turning the sintered tungsten carbide containing 22wt% cobalt. Matras & Kowalczyk, (2016) also compared the cutting force, tool life, and surface roughness of the turning sintered carbide shaft with PCD and CBN tool [13]. The results show that the surface roughness for turning with CBN cutting edges was better than for the results obtained with PCD tools. In this study, we adopted the sintered tungsten carbide workpiece having 25wt% Co with high hardness 82.5 HRA and the CBN inserts. The effects of hard turning process of sintered tungsten carbide were investigated by using Face Central Composition Design. Also, a mathematical model for predicting surface roughness was formulated.

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II. Experimental System and Method

In this study, the experiment was conducted on CNC turning center as shown in Fig. 1. The cutting tools are the TiN coated CBN inserts from DINE tool manufacturer (Korea) with code ISO CNGA120408-DNC250. The workpieces were made by the tungsten carbide YG25C (Zhuzhou Better Tungsten carbide Co.) with hardness 82.5 HRA, having dimensions 50x25x80 mm. The sample properties are shown in table 1. The surface roughness was measured by Mitutoyo SJ210 (Fig. 2).

TABLE I. Properties of Cemented Tungsten Carbide YG25C

Co%	Density (g/cm3)	Hardness HRA	Grain size of WC	Transverse rupture strength T.R.S (Mpa)
25	13.15	82.5	3	26000

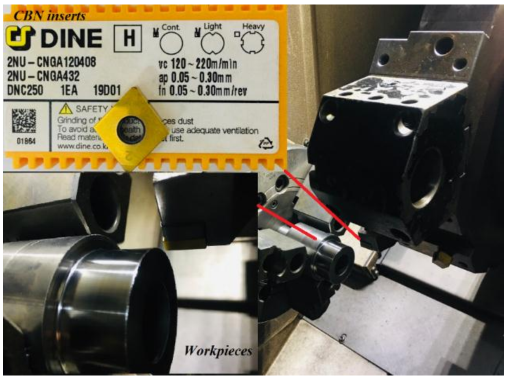

Figure 1. Experimental set up

Figure 2. The surface roughness tester

In this study, cutting speed, feed rate, and depth of cut were selected to study surface roughness. The response surface method with face central composite design (FCCD model) was proposed with 4 corner points, 6-face central points around the center, and added four center points (Fig. 3). The effects of input variables on surface roughness were investigated and the surface roughness prediction model was proposed.

An experimental matrix with the help of Minitab 18 software was given in Table II. The levels of the input parameters which are chosen from the cutting tool manufacturer's recommendations and previous studies are shown in Table III.

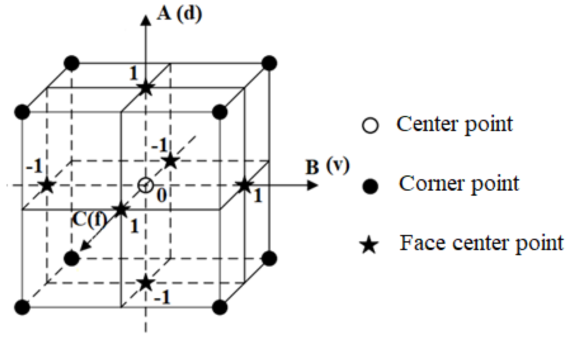

Figure 3. FCCD design

TABLE II. Experimental Matrix

Std Order	Run Order	Pt Type	d (mm)	V (m/min)	f (mm/rev)	Ra (μm)
8	1	1	0.4	70	0.2	2.21
12	2	-1	0.25	70	0.15	0.633
6	3	1	0.4	30	0.2	1.443
19	4	0	0.25	50	0.15	0.566
9	5	-1	0.1	50	0.15	0.533
1	6	1	0.1	30	0.1	0.312
7	7	1	0.1	70	0.2	1.577
2	8	1	0.4	30	0.1	0.363
13	9	-1	0.25	50	0.1	0.19
15	10	0	0.25	50	0.15	0.551
14	11	-1	0.25	50	0.2	1.239
10	12	-1	0.4	50	0.15	0.727
20	13	0	0.25	50	0.15	0.567
17	14	0	0.25	50	0.15	0.571
11	15	-1	0.25	30	0.15	0.727
16	16	0	0.25	50	0.15	0.54
5	17	1	0.1	30	0.2	1.361
3	18	1	0.1	70	0.1	0.224
4	19	1	0.4	70	0.1	0.424
18	20	0	0.25	50	0.15	0.557

TABLE III. Input Parameters and Their Levels

Parameters	Units	Levels		
		-1	0	1
Depth of cut *(d)*	mm	0.1	0.25	0.4
Cutting speed *(V)*	m/min	30	50	70
Feed rate *(f)*	mm/rev	0.1	0.15	0.2

III. Result and Discussion

A. *Analyze the Influence of Cutting Parameters on Surface Roughness*

The experimental trials were conducted by following random experimental order (runOrder) designed by Minitab 18 software. The surface roughness values are listed in Table II. ANOVA results show that the input machining parameters strongly influence on surface roughness (Fig. 4, 5). From Pareto chart, the factors having bars that extend within the reference line are statistically significant. The Pareto chart shows that the effect of square d*d and interaction d*f are not statistically significant. The feed rate has the strongest influence on surface roughness followed by d, V*f, f*f, V, V*V, and d*V.

TABLE IV. ANALYSIS OF VARIANCE

Source	DF	Adj SS	Adj MS	F-Value	P-Value	C %
Model	9	5.12717	0.56969	58.37	0	
Linear	3	4.2004	1.40013	143.46	0	
d	1	0.13433	0.13433	13.76	0.004	2.86
V	1	0.07436	0.07436	7.62	0.02	1.58
f	1	3.99171	3.99171	409	0	84.93
Square	3	0.18593	0.11698	24.28	0	
d*d	1	0.02804	0.02804	2.87	0.121	0.60
V*V	1	0.06295	0.06295	6.45	0.029	1.34
f*f	1	0.09494	0.09494	9.73	0.011	2.02
2-Way Interaction	3	0.21582	0.07194	7.37	0.007	
d*V	1	0.06119	0.06119	6.27	0.031	1.30
d*f	1	0.02703	0.02703	2.77	0.127	0.58
V*f	1	0.1276	0.1276	13.07	0.005	2.72
Error	10	0.0976	0.00976			2.08
Pure Error	5	0.00069	0.00014			
Total	19	4.69975				

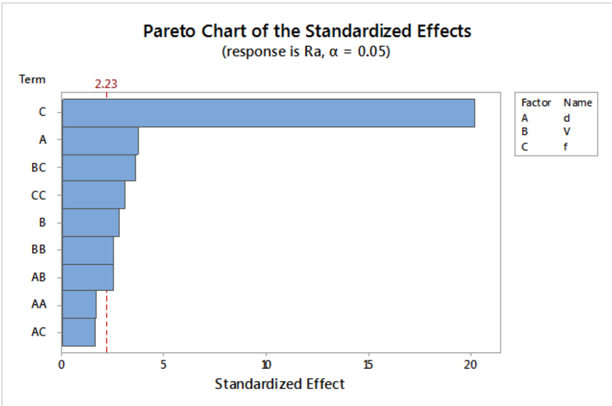

Figure 4. Pareto chart of the standardized effects

Fig. 6 illustrates the influence of cutting parameters to surface roughness. The result shows that the surface roughness values increased rapidly when increasing the feed rate from 0.1 to 0.2 mm/rev. However, the surface roughness increases slowly with the depth of cut from 0.1 to 0.4 mm. Similarly, the mean of surface roughness reaches the minimum value with the cutting speed of about 45 m/min, and surface roughness increases when the cutting speed increase to 70 m/min.

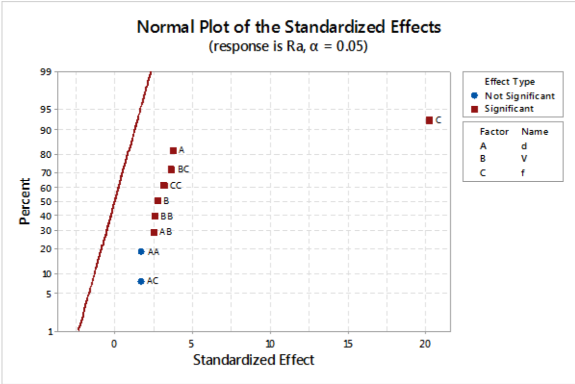

Figure 5. Normal plot of the standrdized effects

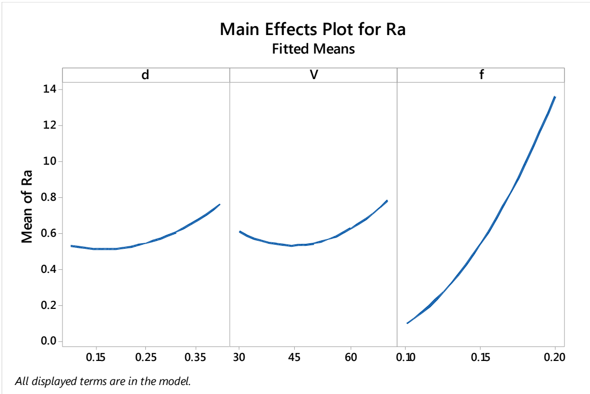

Figure 6. Main effects plot for the surface roughness

These contour plots show the relationship between the cutting parameters used turning WC alloy and the surface roughness with a cutting parameter hold value. Lighter color regions indicate smaller surface roughness. The contour plot in Fig. 7 analysis the effect of feed rate and cutting depth on the surface roughness with the cutting speed of 50 m/min. The results show that surface roughness is maintained at a value when increasing the depth of cut and reducing feed rate respectively.

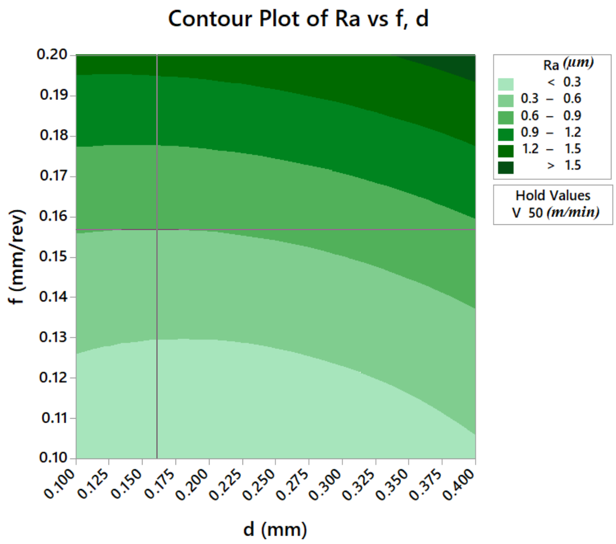

Figure 7. Contour plot of Ra for feed rate and cutting depth

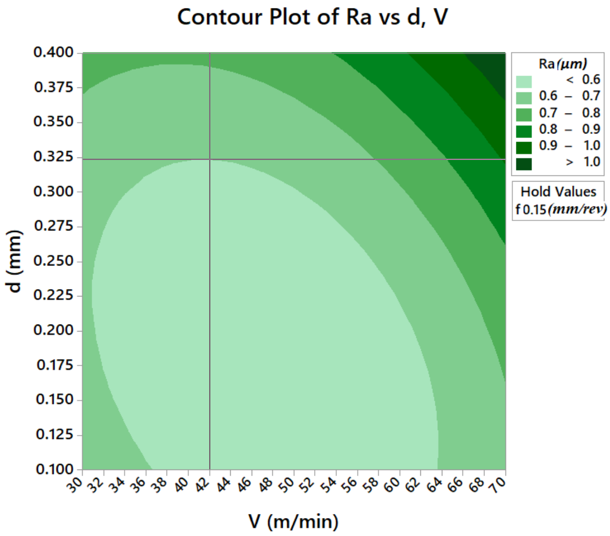

Figure 8. Contour plot of Ra for depth of cut and cutting speed

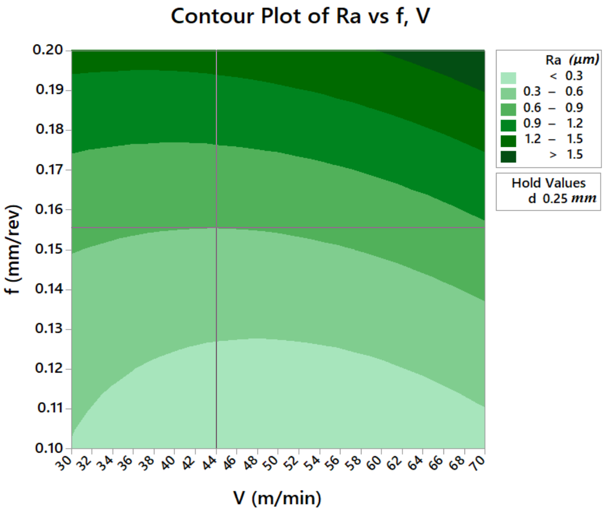

Figure 9. Contour plot of Ra for feed rate and cutting speed

The contour plot analysis for the surface roughness with cutting depth and cutting speed is given in Fig. 8. The results indicated that when holding the feed rate at 0.15 mm/rev, the surface roughness values will be smaller at medium cutting speed and smaller cutting depth. Fig. 9 shows the contour plot for the surface roughness with feed rate and cutting speed. The results indicated that the smaller values of surface roughness will obtain at medium cutting speed and smaller feed rate when holding cutting depth at 0.15 mm/rev.

B. *Predicted Model and Optimization for Surface Roughness*

The prediction model for surface roughness in hard turning of tungsten carbide was built through regression by using the FCCD experimental model with a reliability of 95%. The experimental results show that a reliable and useful statistical model based on ANOVA analysis was formulated. The second-order equation of the surface roughness is related to cutting parameters are described in the following equation:

$$Ra=2.743- 4.09\,d- 0.0597\,V- 17.91\,f+ 4.49\,d*d + 0.000378\,V*V+ 74.3\,f*f+ 0.0292\,d*V+ 7.75\,d*f + 0.1263\,V*f$$

Where Ra (µm) is the surface roughness; V (m/min) is the cutting speed; f (mm/rev) is the feed rate; d (mm) is the cutting depth.

The regression model is shown in Table V with R-square (R-sq) equal to 98.13 %. The value of the adjusted R-square equals to 96.45%, which is a modified version of R-squared that has been adjusted for the number of predictors in the model. The prediction R-square (R-sq (pred)) investigates that the predicted model is supposed to illustrate about 79.78% of the variability in new data and is suitable for the value of the adjusted R-square. Therefore, this mathematical model is suitable for predicting the surface roughness in the hard turning tungsten carbide using CBN inserts.

TABLE V. MODEL SUMMARY

S	R-sq	R-sq (adj)	R-sq(pred)
0.0987916	98.13%	96.45%	79.78%

Optimization of the cutting parameters to reach the minimum surface roughness could be determined by the optimized model using the FCCD design. The optimal cutting conditions are shown in Fig. 10. The optimization plot also shows the effect of different cutting parameters on the surface roughness. The optimum cutting conditions for minimum surface roughness as determined by Response Optimizer Tool were the cutting speed of 55 m/min, the feed rate of 0.1 mm/min, and depth of cut of 0.19 mm. The minimum surface roughness was brought out of 0.0845 µm at these optimal conditions.

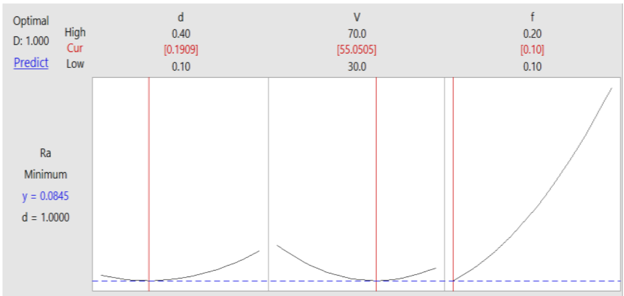

Figure 10. Optimized cutting parameters

IV. CONCLUSION

In this study, face central composite design (FCCD) was used to investigate the effects of input cutting parameters on the objective functions in hard turning of WC in terms of surface roughness. Feed rate is the most powerful influence on the surface roughness in the W-Co 25wt% turning process. A predicted surface roughness model has been determined based on the cutting parameters in this process. An optimized model for surface roughness was also implemented and proposed the optimum set of parameters (V-55 m/min, f-0.1 mm/rev, and d-0.19mm). The minimum surface roughness was estimated as 0.0845 μm at these optimal conditions.

Conflict of Interest

The authors declare no conflict of interest

Author Contributions

Conceptualization, M.T.N and Q.T.N.; methodology, M.T.N and Q.T.N; software, M.T.N.; validation, M.T.N; formal analysis, M.T.N; resources, Q.T.N; data curation, M.T.N; writing—original draft preparation, M.T.N; writing—review and editing, Q.T.N.; visualization, M.T.N.; supervision, M.T.N; project administration, M.T.N.

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Minh Tuan Ngo was born in 1985, in Thai Nguyen city, Viet Nam. He received the B.Sc., M.Sc. and Ph.D degrees from Ha Noi Science and technology university in 2007, 2011 and 2018. He has worked as Design Engineering, Kosaka seiki Company, Aichi province, Japan in the year of 2007 to 2009. And now, he works as a lecturer and researcher of Faculty of Mechanical Engineering in Thai Nguyen university of technology, Vietnam. His main works are gear hobbing process, Machining process optimization, Mechanical engineering, Hard machining process and CAD/CAM-CAE and Software in Mechanical engineering & Design of Experiments (DOE). He acts as a Reviewer in Vietnam Journal of Science and Technology (VJST), TNU Journal of Science and Technology. He authored/co-authored nearly 17 International Journal papers and International Conference papers.

Quoc Tuan Nguyen was born in 1969, in Viet Nam. He received the Ph.D degrees from Ha Noi university of Science and technology in 2003. He is the head of training office and works as a lecturer, reseacher and Associated professor of Faculty of Mechanical Engineering in Thai Nguyen university of technology, Vietnam. His main researchs are Cutting tool design, Hard machining process, Cutting process optimization, nontraditional machining process and CAD/CAM-CAE. He acts as a Reviewer in Vietnam Journal of Science and Technology (VJST), TNU Journal of Science and Technology and Vietnam Mechanics Association & national journals and international journal of science. He authored/co-authored nearly 21 National journal, International Journal papers and International Conference papers.