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Effects of Cutting Parameters on Flank Wear in Hard Turning of Sintered Tungsten Carbide Using CBN Tools

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ABSTRACT: Tungsten carbide has been widely used in dies and molds for metal forming because of its excellent mechanical properties such as high hardness and abrasion resistance, which also create the challenge for conventional cutting processes. Therefore, this work presents the experimental study on the machinability of CBN tools in hard turning process of tungsten carbide material. The response surface design with face central points was used and ANOVA analysis was performed to evaluate the effects of cutting speed, feed rate and depth of cut on the flank wear, tool wear behavior and wear mechanism. The regression function of flank wear was built, and wear mechanism was also studied. The obtained results indicated that the cutting speed has strongest influence on flank wear and wear rate. The set of optimal cutting parameters for minimizing flank wear was determined as cutting speed of 30 m/min, cutting depth of 0.1 mm and feed rate of 0.136 mm/rev. From those, this work will contribute some important technological guides for hard turning process to improve the machining performance and enlarge the applicability in sustainable production.

KEYWORDS: Hard turning, tungsten carbide, tool wear, flank wear, CBN, ANOVA analysis, optimizing

INTRODUCTION

Nowadays, tungsten carbide (WC) is commonly used in the different applications such as cutting tools, die and mold industries because of its good properties such as heat and wear resistance, very high hardness and strength but brittle [1]. Tungsten carbide and its composite are also named as hard metal, so they are grouped in difficult-to-cut materials. The conventional methods for machining tungsten carbide were Electrical Discharge Machine (EDM), Laser-Assisted Machining (LAM) or grinding [2-3]. However, these methods have many limitations such as low productivity, difficult to shape the geometrical flexibility [4]. In addition to that, for grinding, a conventional machining process, it possesses high cost, and environmental issues caused by using cutting fluids are considered the main drawbacks [5].

Hard machining technology, including hard turning, hard milling, hard drilling, and so on, has been studied and developed to overcome this problem and exhibited much more advantages in practice [6, 7]. However, the enormous heat generated from contact zone causes very high rate of tool wear, so the cutting tools are always required to use the high grade like PVD, (P)CBN, ceramic, coated carbide [8-10]. In addition, the selection of cutting inserts and their cutting parameters is crucial to achieve the effective hard cutting processes in terms of technological, economic, and environmental characteristics. In hard machining under dry condition, tool wear is considered as the most important factors to evaluate the economic and technical efficiency. Hence, this factor has gained much attention and many related studies have been made.

The author S.J. Heo [11] studied the effects of the cutting parameters on the wear of PCD tool and cutting forces in hard turning of cemented carbide (WC). This study indicated that the cutting speed has strong effect on tool wear rate. The tool wear of internal hard turning of sintered carbide using PCD inserts was also analyzed N. L. Coppini et al. [12]. The results suggested that by avoiding sudden breakage of the cutting edge in the beginning of tool life, cutting speed should be used above 22 m/min and feed rate should be used below 0.1 mm/rev. Moreover, the values of surface roughness in internal hard turning can achieve as low as those in grinding processes. X. Wu et al. [13] studied the tool wear and its effect on the cutting forces in the micro milling of tungsten carbide with PCD tool. The experimental results showed that the wear is focused on the tool tip and the main wear mechanisms are the adhesive, micro chipping and abrasive wear.

K. Liu et al. [14] investigated the tool wear characteristics of CBN inserts in ductile cutting of tungsten carbide. This research presented that the wear land occurs mainly at flank face. Diffusion, adhesion and abrasion wear are dominated. The tool life is shortened and the tool wear is larger when increasing the cutting speed. M.J. Kim et al. [15] compared the flank wear of a conventional bite and a chamfered bite in hard turning of tungsten carbide process using diamond tool under same cutting conditions. He pointed out that the chamfered bite had the better wear resistance than the conventional bite. The effect of the chamfered length on cutting forces and the strain rate of single-crystal diamond tools were studied and verified by finite element analysis (FEA). The very good surface roughness can be achieved by using the chamfered bite. M. Okada and his co-authors [16] studied the wear mechanisms and characteristics of hard milling of tungsten carbide using a diamond-coated carbide ball end mill.

The tool life significantly reduces with higher feed rate, and the cutting edge temperature reached approximately 440–560°C at spindle revolution of 20,000–30,000 rpm. The diffusion wear was not observed in tungsten carbide cutting, and the adhesion wear was dominant. S. Tsurimoto et al. [17] made the study on the machinability of CBN tool in hard turning of tungsten carbide material. The obtained results showed that that the flank wear of CBN tool reduces with increasing the percent of Cobalt binder, and CBN tool is suitable for cutting the WC carbide with containing larger amount of Cobalt binder. B. Bulla et al. [18] studied hard turning process of binderless, nano crystalline tungsten carbide by using single crystal diamond tools.

The high cutting temperature and stress in contact zone cause the rapid tool wear and tool failure, especially in high cutting speed or very low cutting speed. Hence, the cutting parameters are nescessary to optimize in order to ensure the maximum machining performance of cutting tools as well as the proper tool life. S. Maeng et al. [19] also used PCD tool for hard machining of tungsten carbide material, but, in this work, the author focused on the effect of texturing on the cutting performance in ultra precision machining of WC. The authors found that the texturing on the rake face helps to reduce friction coefficicent about 10%, which decreases the generated heat and prolongs the tool life.

From the above-cited literature, hard machining of tungsten carbide is a new topic and has only been investigated within a few publications. The studies were focused on the tool wear by mainly using diamond tools and some using CBN inserts. For dry hard machining, high cutting temperature is the main factor affecting the wear rate, tool life, and surface quality. Hence, the influence of cutting parameters on the machining performance and the wear behavior are needed to further investigate. This study aims to investigate the wear behavior and the machinability of CBN tools. A central composite design with face central point was applied for optimizing the hard turning of WC process aimed to minimization value of flank wear. The influences of cutting parameters on flank wear of CBN tool in hard turning process are analyzed by ANOVA method. Moreover, the optimization of cutting parameters in term of flank wear (VB) minimization related to wt% Cobalt binder is also investigated.

METHODS AND MATERIALS

The tungsten carbide sample is made by sintered tungsten carbide having 25%wt cobalt binder of Zhuzhou Better company. They have hardness of 82.5 HRA with diameter of 50mm and length of 80mm. The properties of workpiece materials are shown in Table 1. The experimental process was conducted on Mazak Quick Turn Smart 200 Turning Centre (made in Japan) as shown in Figure 1. The ISO CNGA120408-DNC250 CBN inserts of DINE tool manufacturer (Korea) were utilized (Figure 2). The flank wear of CBN tool was measured with machining distance 100m by KEYENCE VHX-7000 Digital Microscope (made in Japan).

In this investigation, the cutting speed, feed rate and depth of cut were selected to study the flank wear. Based on the cutting tool manufacturer’s recommendations and the results of previous studies, the control factors and their levels are shown in Table 2. In order to analyze the effect of cutting parameters on the flank wear, a composite design with the face central points was selected with 18 trials (4 corner trials, 6-face central trials and 4 center points (Figure 3). Minitab 18 software was used to design the experimental matrix (Table 3).

Table 1. Properties of tungsten carbide YG25C

Co %	Density (g/cm^3)	Hardness (HRA)	Grain size (μm)	T.R.S (Mpa)
25	13.15	82.5	3	26000

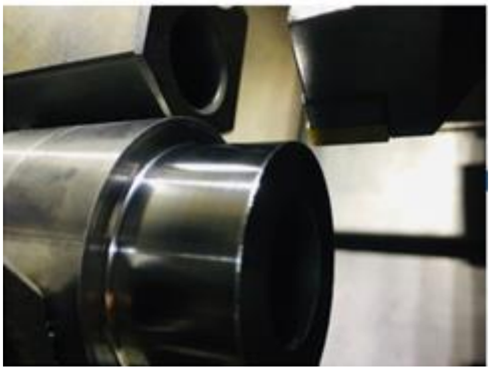


Figure 1. Experimental set up

Figure 2. The ISO CNGA120408-DNC250 CBN insert

Table 2. Control factors 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

Table 3. The experimental matrix and results

Std Order	**Run Order**	**d (mm)**	**V (m/min)**	**f (mm/ rev)**	**VB (μm)**
8	1	0.4	70	0.2	355.9
12	2	0.25	70	0.15	326.7
6	3	0.4	30	0.2	170.5
19	4	0.25	50	0.15	237.7
9	5	0.1	50	0.15	186.0
1	6	0.1	30	0.1	147.8
7	7	0.1	70	0.2	285.8
2	8	0.4	30	0.1	181.9
13	9	0.25	50	0.1	214.0
15	10	0.25	50	0.15	235.0

14	11	0.25	50	0.2	282.2
10	12	0.4	50	0.15	219.4
20	13	0.25	50	0.15	235.8
17	14	0.25	50	0.15	237.4
11	15	0.25	30	0.15	189.2
16	16	0.25	50	0.15	236.5
5	17	0.1	30	0.2	163.4
3	18	0.1	70	0.1	307.0
4	19	0.4	70	0.1	350.5
18	20	0.25	50	0.15	236.8

RESULTS AND DISCUSSION

A response surface model with face central points was designed by using Minitab 18 software. ANOVA analysis was performed with 5% significance level. The effects of cutting parameters on flank wear are given by the following equation with the coefficient of determination (R^2) equal to 96.29%.

$$VB= 227.8 + 637*d - 2.88*V - 1634*f - 1324*d*d + 0.0637*V*V + 6247*f*f + 3.02*d*V - 7*d*f- 2.50*V*f$$

The ANOVA results shown in Table 4 indicated that cutting speed is the most significant factor affecting tool wear, followed by feed rate and cutting depth. The interaction effects exhibit less influence on tool wear. The pareto chart in Figure 3 shows the effect level of the investigated factors on the flank wear basing on the average of standardize effect. Standardized effect sizes help you evaluate how big or small an effect is when the units of measurement are not intuitive. The parameters strongly affecting on the output parameters have a standardized effect greater than the average (2.23). From Figure 3, it can be seen that the cutting speed, cutting depth and their square strongly influence on the flank wear.

Table 4. Analysis of Variance

Source		Adj SS	Adj MS	F- Value	P- Value
Model	9	68278.3	7586.5	28.86	0.000
Linear	3	63630.6	21210.2	80.69	0.000
d	1	3541.9	3541.9	13.47	0.004
V	1	59768.4	59768.4	227.38	0.000
f	1	320.4	320.4	1.22	0.295
Square	3	3942.4	1314.1	5.00	0.023
d*d	1	2439.1	2439.1	9.28	0.012
V*V	1	1783.7	1783.7	6.79	0.026
f*f	1	670.8	670.8	2.55	0.141
2-Way	3	705.2	235.1	0.89	0.477
d*V	1	655.2	655.2	2.49	0.145
d*f		0.0	0.0	0.00	0.993
V*f		50.0	50.0	0.19	0.672
Error	)	2628.5	262.9		
Pure Error		38.6	7.7		
Total	)	70906.8			

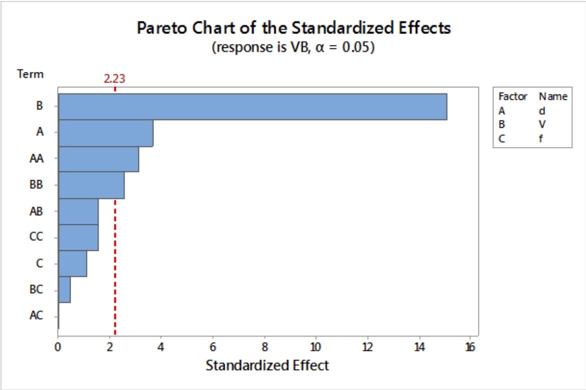


Figure 3. The pareto chart for the flank wear of CBN inserts

Figure 4 describes the main influence of investigated parameters on the average value of flank wear. Main effects plot indicated that the tool wear increases rapidly with the rise of cutting speed. Besides, tool wear increases slowly when increasing the cutting depth and reaches the largest value with the cutting depth about 0.3mm. The feed rate causes very small influence on tool wear.

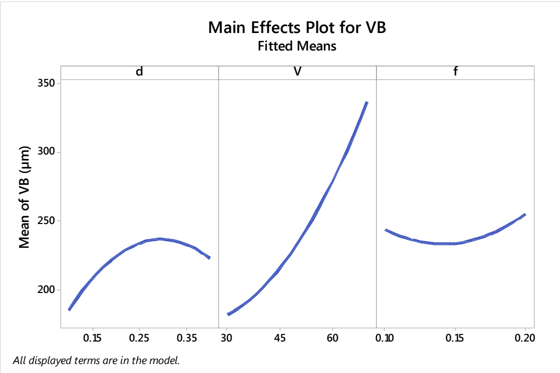
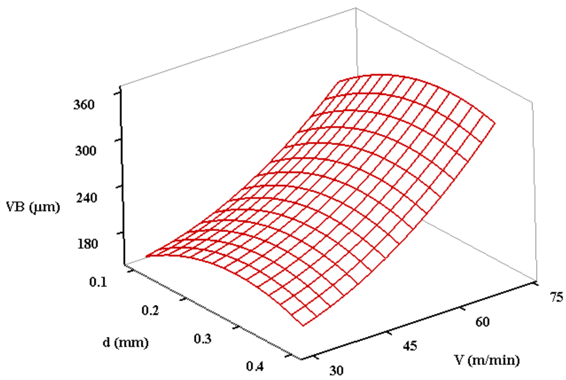
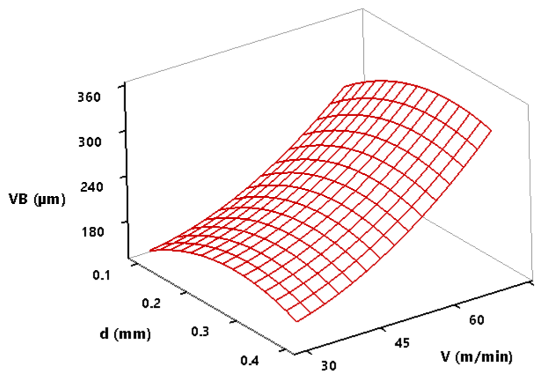


Figure 4. Main effects of the cutting parameter on the flank wear

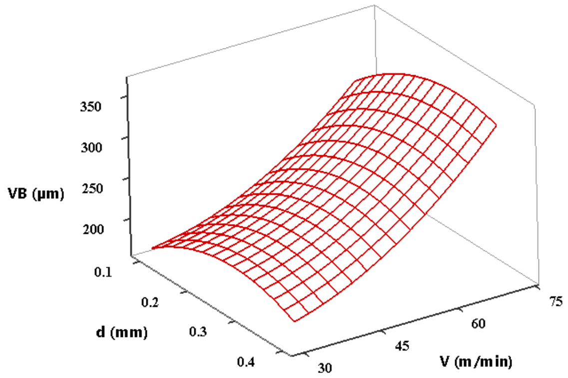
The surface plots presenting the relation of the cutting speed, depth of cut and flank wear with different feed rates are shown in Figure 5. From the obtained results, it can be clearly seen that the values of tool wear increase significantly when rising the cutting speed, but they changes very little with the variation of depth of cut. In detail, increasing the depth of cut from 0.1 mm to 0.3mm would increase the tool wear, but the tool wear would decrease with the change of cutting depth from 0.3mm to 0.4mm.



a, Surface Plot of VB vs V, d (Hold f 0.1mm/rev)

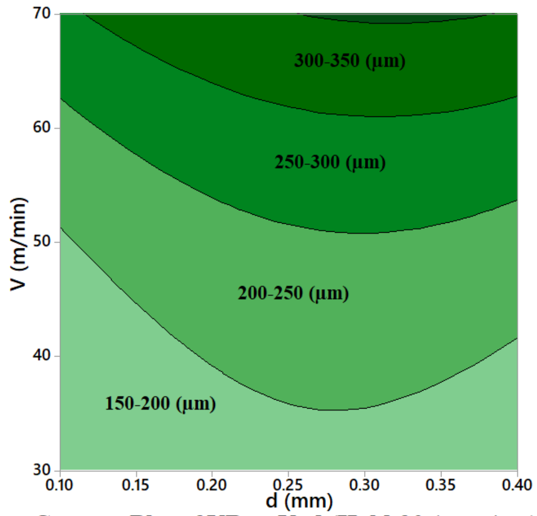


b, Surface Plot of VB vs V, d (Hold f 0.15 mm/rev)

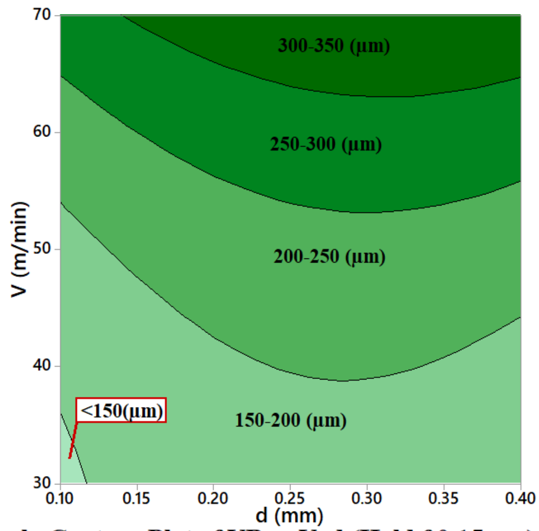


c, Surface Plot of VB vs V, d (Hold f 0.2 mm/rev)

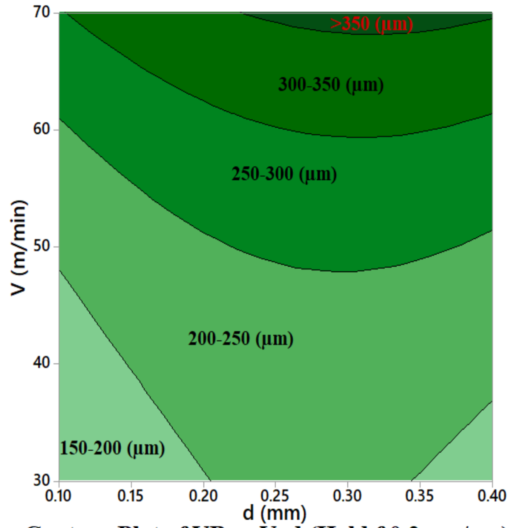
Figure 5. Surface plots for flank wear



a, Contour Plot of VB vs V, d (Hold f 0.1 mm/rev)



b, Contour Plot of VB vs V, d (Hold f 0.15mm)



c, Contour Plot of VB vs V, d (Hold f 0.2mm/rev)

Figure 6. Contour plots for flank wear

Figure 6 presents contour plots of flank wear with the three levels of feed rate using the Face Central Composition model. Studying the plots, the combination of the feed rate of 0.15 mm/rev, the cutting speed about 30-35 m/min and the depth of cut of 0.1 mm contributes to the smallest value of tool wear (less than 150 µm). In the case of holding feed rate of 0.1 mm/rev, the tool wear ranges from 150-200 µm when choosing the cutting speed within 30-50 m/min and cutting depth of 0.1-0.4 mm. For the feed rate of 0.15 mm/rev, the tool wear ranges from 150-

200 µm when choosing the cutting speed of 30-55m/min and the cutting depth of 0.1-0.4mm. For the feed rate of 0.2 mm/rev, tool wear can be maintained of around 150-200 µm when the cutting speed is less than 48 m/min and the cutting depth is less than 0.2 mm, or the cutting speed is less than 35 m/min and the cutting depth is greater than 0.35 mm.

The optimization of cutting parameters for the flank wear

The optimal parameters for the flank wear are determined by using the response optimizer in Minitab. The minimized response is selected for the objective function, because the smaller flank wear is better. The optimized result is illustrated in Figure 7. The flank wear will reach to the minimum value (141.26 µm) with the cutting depth of 0.1mm, the cutting speed of 30 m/min, and the feed rate of 0.1364 mm/rev.

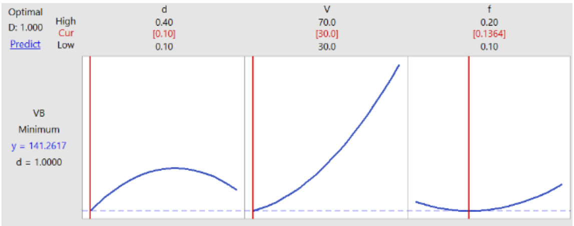


Figure 7. The optimization of cutting parameters

Tool wear investigation

After studying the flank wear with the different machining parameters, the wear mechanism is also investigated. From Figure 8, the abrasive wear is the main wear mechanism in cutting tungsten carbide using CBN tools. The wear land concentrates in the cutting edge. The main reason is the enormous heat generated from cutting zone combined with the very high hardness of tungsten carbide workpiece, which promotes the wear rate.

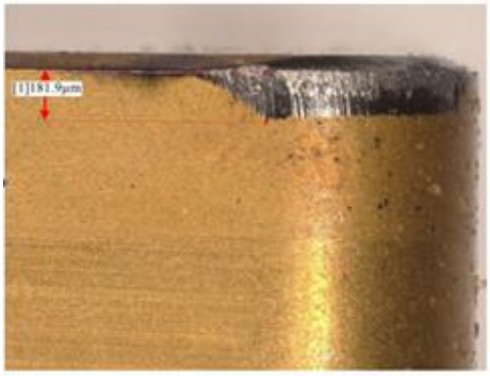


Figure 8. Tool wear investigation

CONCLUSION

In this paper, an experimental study is made to analyze the effects of cutting parameters including cutting speed, cutting depth, and feed rate on the tool wear behavior in hard turning process of sintered tungsten carbide using CBN tool. A response surface model with face central points was designed by using Minitab 18 software. ANOVA analysis was performed with 5% significance level to investigate the effect of input machining parameters and optimize them. From the experimental results, the cutting speed has a strongest effect on the flank wear. Although cutting speed with low ranges (<30 m/min) and other factors have been analyzed in several previous studies, the effects of the depth of cut and higher cutting speed have rarely been found in literature. It has been found that, varying depth of cut also results in changing the flank wear. Also, the abrasive wear is the main wear mechanism. A predicted flank wear model is built up. An optimized model for flank wear was also implemented and proposed the optimum set of cutting parameters (cutting speed V=30 m/min, feed rate f=0.136 mm/rev, and depth of cut d=0.1mm).

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