Multi-response Optimization and Analysis Wear Mechanism of CBN Inserts in the Tungsten Carbide Hard Turning Process

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***Abstract*—Tungsten carbide is a compound of tungsten and carbon which has high compressive strength and hardness. Therefore, Tungsten carbide is widely used in manufacturing tools, dies, and rollers. This paper researches to determine the optimal set of machining parameters and analyze the surface roughness and the wear mechanism when turning carbide materials using CBN inserts. A face central composite model is used to determine the optimal cutting parameter with minimum surface roughness, minimum flank wear, and both. Verification experiments with those three sets of optimal cutting parameters were performed. The tool wears characteristics for the three optimal cutting modes are also analyzed. The results show that mechanical abrasion, scratching, and wear due to adhesion occurs when machining carbide inserts. As the cutting speed increases, the wear due to adhesion increases.**

***Keywords*—hard turning, Tungsten carbide, multi-response, optimization, surface roughness, flank wear**

I. INTRODUCTION

Sintered Tungsten Carbide is a super-hard material that retains abrasive resistance and is being used in the manufacture of tools, dies, punches, rolling pins, etc [1]. Recently, sintered tungsten carbide is being used as an alternative to alloy steels or powder metallurgy steels to improve the life of molds and rollers. The outstanding property of sintered Tungsten carbide is that it has a high hardness above 80HRA and has a high elastic modulus, thereby reducing its machinability [2]. Recently, researchers have proven that complex tungsten carbide parts can be made by additive techniques [3].

Currently, mainly sintered Tungsten carbide materials are processed by grinding, polishing, Electrical Discharge Machining (EDM), and Electrochemical Machining (ECM) methods. However, a major limitation of these methods is low productivity and limited forming capacity. Therefore, many machining methods such as turning and milling are studied and applied in the processing of sintered Tungsten carbide. Liu *et al.* have studied the processing of tungsten carbide materials using CBN cutting tools [4]. Research has shown that when the depth of cut is less than a critical value, the ability to cut tungsten carbide materials is the easiest. In 2003, the effects of hard turning parameters in machining sintered tungsten carbide using PCD tools on the flank wear and cutting force were studied by Heo *et al* [5]. The researched results indicated that the cutting speed is the most significant parameter with the tool wear in the hard turning WC using PCD inserts.

In 2013, the influence of cutting parameters on surface roughness in the hard turning process of WC alloys was studied by Coppini *et al*. (2013) [6]. Research has shown that the cutting speed is the most influential factor on surface roughness. However, this study only used the two-level experimental model, so the optimal set of parameters has not been given. Kim *et al*. (2012) also analyzed the influence of the chamfer angle of the cutting edge on the surface roughness in the turning process of WC alloys by both simulation and experimental models [7]. The research results show that the surface roughness is better when using a chamfer insert compared to using a traditional insert. Many researcher also analyzed the effects of cutting parameters on surface roughness in WC–Co turning process PCD inserts [8]–[10]. In 2012, the researched results of Tsurimoto *et al.* showed that a CBN tool with a particle size 1 μm is suitable for machining a sintered tungsten carbide with 11% wt Co [11]. The study also showed that the flank wear increased with decreasing the content % wt Co.

In 2016, the efficiency of the hard turing WC alloy with PCD and CBN inserts was studied by Matras & Kowalczyk [12]. The researched results show that PCD inserts are more effective in machining WC 15% wt Co alloy, while CBN inserts are suitable for the machining process of WC alloy with 25% wt Co. In the same year, the flank wear and cutting force during machining tungsten carbides using a diamond coated ball end mill were studied and analyzed [13]. Surface roughness in internal turning using PCD insert was studied and compared with grinding process [14]. Research results show that the surface quality in the turning tungsten carbide process is equivalent to the grinding process. The influences of the tool wear on the cutting force in the micro milling of tungsten carbide using PCD tool were

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analyzed by Wu *et al.* (2018) [15]. This research invetigated the mechanism wear of PCD tool in the micro milling proccess of tungsten carbide. In this study, the optimal sets of cutting parameters for each objective and multi objectives are determined. The mechanism of CBN tool wear when machining with the optimal parameter sets is analyzed.

II. Experimental System and Method

In this study, experiments were carried out on a CNC lathe center of Mazak (Japan) at the metal cutting laboratory of Thai Nguyen university of technology. The workpieces were made by the high hardness tungsten carbide alloy (82.5HRA) with 25%wt Co, which is made by the tungsten carbide YG25C (Zhuzhou Better Tungsten carbide Co.). The cutting tools were the TiN based coated CBN inserts with ISO code CNGA120408-DNC250 from the DINE tool manufacturer (Korea), Fig. 1. The surface roughness was measured with each trials by Mitutoyo's SJ210 roughness gauge (Fig. 2). The flank wear of CBN tool are measured with machining distance 100m by the by digital microscope VHX–7000 by Keyence (Fig. 3). The tool wear was captured and analyzed by using a scanning electron microscope with an Energy–dispersive X-ray spectroscopy (JEOL JSM–7600F) made in the USA (Fig. 4). The value levels of the cutting parameters in the turning process were selected basing on the proposal of the cutting tool manufacturer (DINE) and the results of previous studies and shown in Table I.

TABLE I. The Value Levels of the Input Factors

Parameters	Units	Levels		
		−1	0	1
Cutting depth *(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

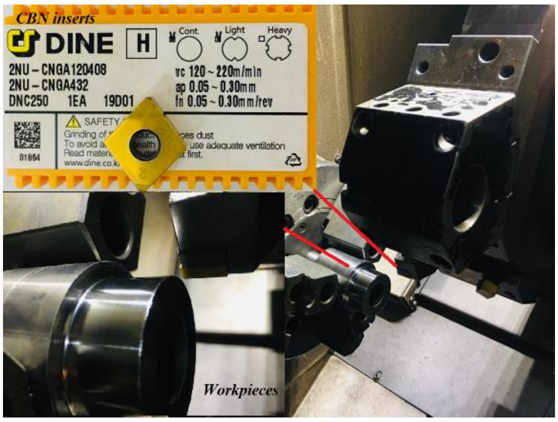

Figure 1. Experimental set up

Figure 2. The surface roughness tester

Figure 3. Digital microscope VHX-7000 by Keyence

Figure 4. Scanning electron microscope -JEOL JSM-7600F

For the purpose of determining the optimal set parameters, an experimental matrix with 18 trials was built using the Response surface methodology with face central composite design (RSM–FCCD). All trials were performed with random experimental order (runOrder) designed by Minitab 18 software and the measurement results are shown in Table II.

TABLE II. THE EXPERIMENTAL MATRIX AND RESULTS

Std. Order	Run Order	d (mm)	V (m/min)	f (mm/rev)	VB (μm)	Ra (μm)
12	1	0.25	70	0.15	326.7	0.633
10	2	0.4	50	0.15	219.4	0.727
14	3	0.25	50	0.2	282.2	1.239
1	4	0.1	30	0.1	147.8	0.312
19	5	0.25	50	0.15	237.7	0.566
7	6	0.1	70	0.2	285.8	1.577
3	7	0.1	70	0.1	307	0.224
5	8	0.1	30	0.2	163.4	1.361
13	9	0.25	50	0.1	214	0.190
20	10	0.25	50	0.15	230.1	0.567
4	11	0.4	70	0.1	350.5	0.424
8	12	0.4	70	0.2	355.9	2.210
15	13	0.25	50	0.15	235	0.551
17	14	0.25	50	0.15	233.4	0.540
11	15	0.25	30	0.15	189.2	0.727
9	16	0.1	50	0.15	186	0.533
18	17	0.25	50	0.15	237.2	0.557
16	18	0.25	50	0.15	234	0.571
6	19	0.4	30	0.2	170.5	1.443
2	20	0.4	30	0.1	181.9	0.363

III. RESULT AND DISCUSSION

A. *Analysis of Variance (ANOVA)*

Analysis of variance was conducted to evaluate the statistical significance of the fit regression model and the influence of the survey factors on the two objective functions Vb and Ra. The ANOVA results in Table III&IV reveal that the quadratic model is statistically significant for the surface roughness and the tool wear of the tungsten carbide machining process. Significant model terms were identified at 95% significance level. The goodness of fit was evaluated from adjusted sums of squares (Adj SS) and Adjusted mean squares (Adj MS) to check the reliability and precision of the model. The probability value (P) for the model is less than 0.05 which indicates that the model is significant, which is desirable as it indicates that the terms in the model have a significant effect on the response.

In the case of surface roughness the Model F-value of 58,37 implies the model is significant. The P value is less than 0.0500 indicate model terms are significant. In this case, đepth of cut (d), cutting speed (V), feed rate (f), V×V, f×f, d×V, and V×f are significant model terms. R^2 =98.13% which is close to one and desirable, which shows that the model explains this much percentage of the variability of the result. The regression model of surface roughness Ra with R^2 equal to 87.76% is given below in Equation:

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

TABLE III. THE ANOVA RESULTS FOR THE SURFACE ROUGHNESS

Source	DF	Adj SS	Adj MS	F-Value	P-Value	
Model	9	5.127 17	0.5696 9	58.37	0.000	Significant
Linear	3	4.200 40	1.4001 3	143.46	0.000	Significant
d	1	0.134 33	0.1343 3	13.76	0.004	Significant
V	1	0.074 36	0.0743 6	7.62	0.020	Significant
f	1	3.991 71	3.9917 1	409.00	0.000	Significant
Square	3	0.710 95	0.2369 8	24.28	0.000	Significant
d×d	1	0.028 04	0.0280 4	2.87	0.121	Not significant
V×V	1	0.062 95	0.0629 5	6.45	0.029	Significant
f×f	1	0.094 94	0.0949 4	9.73	0.011	Significant
2-Way Interaction	3	0.215 82	0.0719 4	7.37	0.007	Significant
d×V	1	0.061 19	0.0611 9	6.27	0.031	Significant
d×f	1	0.027 03	0.0270 3	2.77	0.127	Not significant
V×f	1	0.127 60	0.1276 0	13.07	0.005	Significant
Error	10	0.097 60	0.0097 6			
Total	19	5.224 77				

TABLE IV. THE ANOVA RESULTS FOR THE FLANK WEAR

Source	DF	Adj SS	Adj MS	F-Value	P-Value	
Model	9	68278.3	7586.5	28.86	0.000	significant
Linear	3	63630.6	21210.2	80.69	0.000	significant
d	1	3541.9	3541.9	13.47	0.004	significant
V	1	59768.4	59768.4	227.38	0.000	significant
f	1	320.4	320.4	1.22	0.295	Not significant
Square	3	3942.4	1314.1	5.00	0.023	significant
d×d	1	2439.1	2439.1	9.28	0.012	significant
V×V	1	1783.7	1783.7	6.79	0.026	significant
f×f	1	670.8	670.8	2.55	0.141	Not significant
2-Way Interaction	3	705.2	235.1	0.89	0.477	Not significant
d×V	1	655.2	655.2	2.49	0.145	Not significant
d×f	1	0.0	0.0	0.00	0.993	Not significant
V×f	1	50.0	50.0	0.19	0.672	Not significant
Error	10	2628.5	262.9			
Total	19	70906.8				

In case of flank wear the Model F-value of 28,86 implies the model is significant. In this case d, V, d×d, V×V are significant model terms. The ANOVA table for regression model indicated that the model is significant at $p < 0.0001$. The desirable value of R^2 is 96,29% shows that this much percentage of the variability of result is explained by the model. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. In this case Adeq Precision ratio of 16, 21 indicates an adequate signal. This model can be used to navigate the design space. The following equation are the final empirical models for the response Vb.

$$VB=219.6+649d-2.75V-1570f-1347d\times d+0.0623\ V\times V+6033\ f\times f+3.02\ d\times V-7\ d\times f-2.50\ V\times f$$

B. Optimization of Response and Experimental Verification

Applying the optimization function in Minitab software, the optimal parameters for each response (surface roughness and flank wear) and multi responses are determined. The minimization objective is selected for both surface roughness and flank wear. The results of minimizing surface roughness indicated that the surface roughness value reaches a minimum value of 0.0845 with a cutting speed 55 m/min, a feed rate 0.1 mm/rev and a depth of cut 0.19 mm. The results of minimizing flank wear showed that the flank wear of CBN insert reaches a minimum value of 141.26 µm with a cutting speed 36 m/min, a feed rate 0.136 mm/rev and a depth of cut 0.1 mm. The results of multi responses optimization with the two targets of surface roughness and flank wear showed that when machining with a cutting speed 36 m/min, the feed rate 0.11 mm/rev and depth of cut 0.1 mm can simultaneously guarantee two targets for surface roughness (0.337 µm) and flank wear (154 µm).

The set of optimal cutting parameters for surface roughness, flank wear and simultaneous optimization of two objectives were used for machining in three verification experiments. The results of surface roughness measurement and flank wear are shown in Table V. The results show that the error between the measured surface roughness value and the value predicted by the model is 14.1% when turning with the optimal set of cutting parameters for the smallest surface roughness value. When turning with the optimal set of technological parameters for the flank wear, the error between the measured surface roughness value and the value predicted by the model is 13.7%. When turning with the optimal set of technological parameters for two targets (flank wear and surface roughness), the error between the measured surface roughness value and the value predicted by the model is 11.6% and the error between the measured flank wear and the value predicted by the model is 4.8%.

TABLE V. THE PARAMETERS AND RESULTS OF THE VERIFICATION EXPERIMENTS

No.	V (m/ min)	d (mm)	f (mm/ rev)	predicted		verification	
				VB (µm)	Ra (µm)	VB (µm)	Ra (µm)
EXP.1 (Ra min)	55	0.19	0.1	-	0.085	234.2	0.097
EXP.2 (VB min)	30	0.1	0.14	141.3	-	148.1	0.946
EXP.3 (Ra&VB min)	36	0.1	0.11	154.0	0.336	175.1	0.375

To analyze the tool wear mechanism when machining sintered tungsten carbide, the image of flank wear and EDS analysis were performed on a scanning electron microscope. The results are shown in Figs. 5–10.

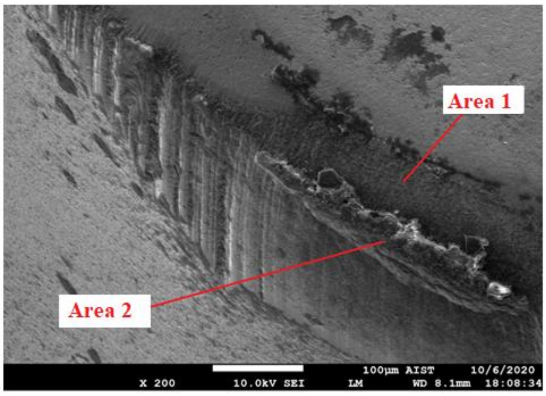

Figure 5. The image SEM for the experiment 1

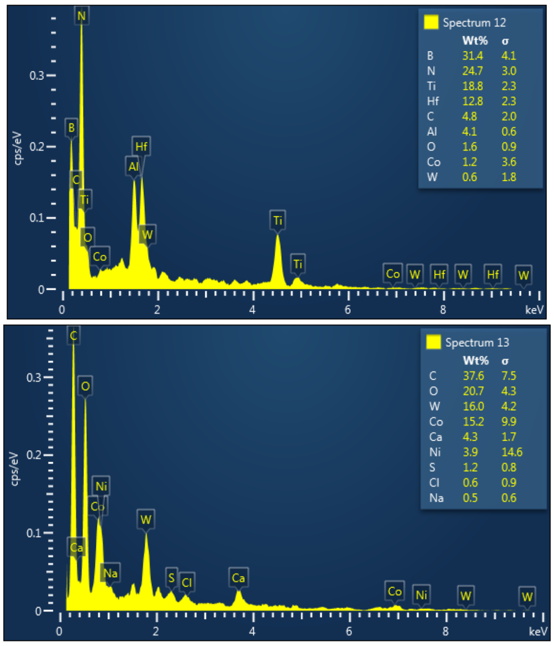

Figure 6. The EDS analysis results for the Experiment 1

The image of the flank wear in Experiment 1 (Fig. 5) shows that there are parallel scratches on the rear face, and there is also an adhesion phenomenon on the top of the cutting edge. Thus, when cutting at high cutting speeds in dry machining conditions, the cutting heat is large, causing the carbide particles to adhere to the top of the cutting edge. In addition, due to the large cutting force, the cutting temperature is high, and elastic deformation of the workpiece may occur, causing scratches on the rear face. EDS analysis was performed in region 1, region 2, and the results are shown in Fig. 6. The results show that there is a high Ti content and high composition BN. This indicates that the abrasion phenomenon of the TiN coating layer has occurred on the rake face of CBN inserts. The high amount of C, W, and Co elements on the adhesion layer indicates that there is the adhesion of workpiece material (WC) on the tip of the cutting edge. The reason is that when cutting with a relatively high cutting speed (55 m/min) in dry machining conditions, the cutting heat increases greatly causing the carbide particles to separate, scratch on the rake face, and at the same time, the amount of molten Co becomes an adhesive that easily adheres to the cutting edge.

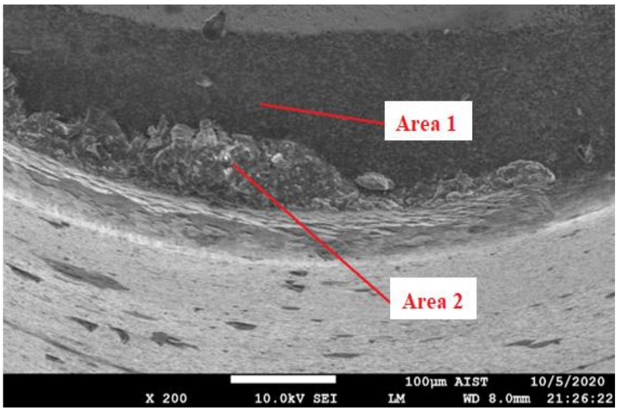

Figure 7. The image SEM for the Experiment 2

The image of the flank wear in Experiment 2 is shown in Fig. 7. The results show that mechanical wear, cracking and coating peeling occur mainly when cutting with low cutting speed (30m/min), depth of cut 0.1 mm and feed rate 0.14 mm/rev. Adhesion of workpiece material on the top of the cutting edge also begins to occur, but in very small amounts. The results of EDS analysis for region 1 and 2 of the tool wear in experiment 2 are shown in Fig. 8. The analysis results show that the Ti component in region 1 is quite large (30.6wt%), indicating that the TiN coating has not worn off yet. In region 2, there is a significant amount of W (7.9 wt%) and Co (12.1 wt%) elements, indicating adhesion of a small amount of tungsten carbide on the tip of the cutting edge. For example, when cutting with a low cutting speed (30 m/min), mechanical wear mainly occurs and wear due to adhesion may occur.

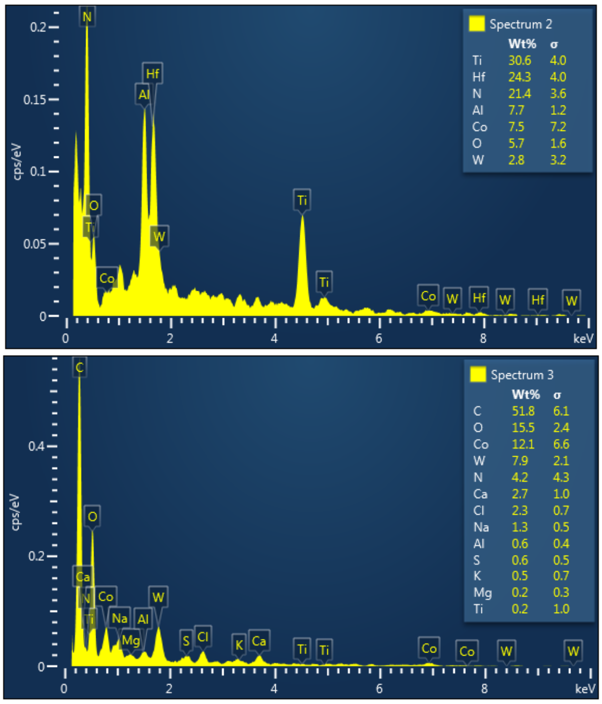

Figure 8. The EDS analysis results for the experiment 2

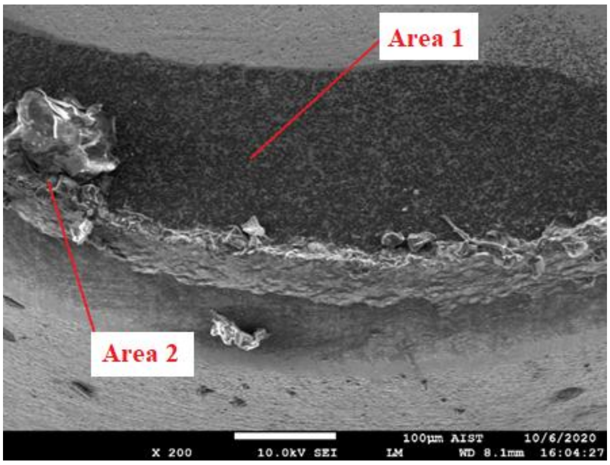

Figure 9. The image SEM for the Experiment 3

The image of the tool wear in Experiment 3 (Fig. 9) shows that abrasion wear and peeling of the coating layer occurs on the rear face, there is also adhesion on the top of the cutting edge. The results of EDS analysis for region 1 and 2 of the cutting tool in Experiment 3 are shown in Fig. 10. The results show that a large amount of elements B (31.4 wt%) and N (24, 7wt%). While the ratio element Ti on the rake face of cutting tool is still significant (3 wt%), but smaller than Experiment 1. This indicates that the coating has started to wear. The adhesion layer of the workpiece material occurs mainly in zone 2. EDS analysis results also show a significant amount of elements W (17.2 wt%) and Co (24.6 wt%) in the adhered material region on the top of the cutting edge.

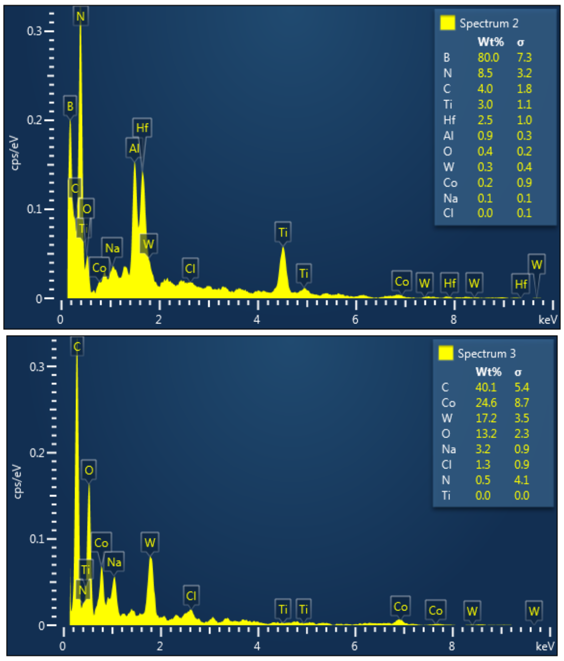

Figure 10. The EDS analysis results for the experiment 3

IV. Conclusion

This study uses a Response surface methodology with face central composite design (RSM–FCCD) to determine the optimal set of the machining parameters with single–objective and multi-objective optimization. Verification experiments with the sets of the cutting parameters are performed. Summarizing the main features, the following conclusions could be presented:

The optimal set of parameters including a cutting speed of 55 m/min, feed rate of 0.1 mm/rev a depth of cut 0.19 mm will bring out the minimum surface roughness Ra = 0.0845 µm.

The flank wear of CBN inserts reaches a minimum value of 141.26 µm with a cutting speed 36 m/min, a feed rate 0.136 mm/rev and a depth of cut 0.1 mm.

The multi responses optimization with the two targets of surface roughness and flank wear indicated that when machining with a cutting speed 36 m/min, the feed rate 0.11 mm/rev and depth of cut 0.1 mm can simultaneously guarantee two targets for surface roughness (0.337 µm) and flank wear (154 µm).

The error between the surface roughness value and the tool wear measured compared to the predicted value is acceptable (less than 15%).

When machining with a set of parameters that ensure the minimum surface roughness, abrasion, scratch wear, and adhesion occurs mainly.

When machining with a parameter set that ensures the minimum flank wear, mechanical wear, cracking and coating peeling occur mainly.

When machining with a set of parameters that ensure that both surface roughness and back wear are minimized, abrasion wear and peeling of the coating layer occurs on the rear face, and there is also adhesion on the top of the cutting edge.

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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