Size Effects of Nana-to-Micro Particles of cBN coated with TiN Matrix on WC Substrate for Hard Turning Applications

Wasawat Nakkiew,[1*] Chunghorng Richard Liu,[2] and Wenping Jiang[3]

[1]Department of Industrial Engineering, Chiang Mai University, Thailand.
[2]Department of Industrial Engineering, Purdue University, United States.
[3]NanoMech LLC, United States.

*Corresponding author: E-mail: wasawat@eng.cmu.ac.th

ABSTRACT

An innovative two-stage composite coating method, which comprises of Electrostatic Spray Coating (ESC) and Chemical Vapor Infiltration (CVI) has been developed by the University of Arkansas and NanoMech, LLC for coating cutting tools in hard turning. For a coated cBN-TiN composite tool, ESC of nano-to-micron cBN particles is sprayed on WC substrate to create a porous matrix, and then CVI is used to infiltrate TiN through this cBN porous matrix to form a very dense coating. Two sizes of cBN particles (cBN particle < 0.5 μm and cBN particle < 2 μm) are used in this paper for investigating effects of coated particle sizes on cutting performances and microstructures of the coating layers. Since tool life is one of several criteria for evaluating cutting tool's performances, tool life studies of tools with two different coated cBN particle sizes are performed. The results show that a coated cutting tool with a smaller coated cBN particle size has a comparative tool life as solid Polycrystalline Boron Nitride (PCBN) tool which is a dominant tool in hard turning applications and the tool life twice as long as a coated tools with larger cBN particle size. Microstructures of coated layers for the tool with smaller cBN particle size at the flank location show a more uniform coating than the coated tool with larger cBN size. A regression analysis model for the tool life of coated composite tools with cBN particle size less than 0.5 μm is constructed as a demonstration for a mean to predict a tool life of cutting tool in metal cutting.

Keywords: Composite coated tool, hard turning, tool life

INTRODUCTION

A concept of using single-step dry turning of hardened steels has been proven for its feasibility as a finish process to compete with grinding and other finish processes (Liu and Mittal, 1995). Finish surface quality obtained from hard turning process is comparable to grinding process and other finish processes (Jochmann and Wirtz, 1999), (Abrao and Aspinwall, 1996). Moreover, hard

turning process has a potential to save significant cost from less capital investment and less manufacturing lead time due to the reduction of steps in producing parts (Liu and Mittal, 1996), (Konig et al., 1993). Short cycle times and greater flexibility in multiple machining operations through CNC lathes in hard machining offers higher productivity than the cost-intensive grinding, precision grinding, and honing operations (Wick, 1988), (Bossom, 1990). Therefore, hard turning has gained increased attention.

The use of polycrystalline cubic boron nitride (PCBN) cutting tool in hard turning has been investigated for a considerable time and it has found increased applications in industry (Halpin et al., 2005), (Tamizharasan, 2006). In addition, substantial investigation of surface integrity aspects of hard machine surface had been present in Agha and Liu (2000) and Liu and Mittal (1998). Despite the fact that solid PCBN tool has a longer tool life than others, the cost of PCBN tool is expensive and it has the tendency of chipping as reported by Chou and Evans (1999).

A two-stage composite coating method for carbide cutting tools had been developed (Russell et al., 2003). The cBN-TiN composite coating was synthesized in two-step process of electrostatic spray coating (ESC) of cBN particles on the substrate of interest to form a porous powder coating, followed by chemical vapor infiltration (CVI) of ceramic binder (TiN). In ESC process, commercially available cBN powder were sprayed from an electrostatic spray gun with the assistance of a jet mill and charged negatively. The charged particles deposited on the grounded substrate by following the electrostatic field lines and formed a uniform porous powder coating. Coating thickness and uniformity were optimized by experimenting with process parameters including electrode-to-substrate distance (100-200 mm), electrical voltage (30-90 kV), pressures (pushing nozzle and grinding nozzles, 30-90 psi) for jet mill, and rotational speed of sample stage (200-450 rpm). The ESC deposited cBN particles are only loosely bonded to each other and to the substrate by electrostatic forces. To make it a dense and functional coating, a CVI process is required to consolidate the porous cBN for a composite coating. CVI works on the same principle as a CVD process. In this case, TiN was infiltrated for cBN-TiN composite coating.

Study of effects of coated cBN particle size on cutting tool's performances and microstructure of coated layers can provide a better understanding and improvement for the composite coating process. Therefore, the tool life study cBN-TiN coated on WC cutting tools with different cBN particle sizes and microstructure analysis of coated layer by using Scanning Electron Microscope (SEM) are performed.

METHODOLOGY

Three types of cutting tool inserts were used in this study as the following:

Tool 1: SNMA 432 cBN-TiN coated inserts. The coating thickness is about 15 μm, with cBN (0-0.5 μm) and the volumetric ratio of about 42-47%.

The substrates are standard WC-Co.

Tool 2: SNMA 432 cBN-TiN coated inserts. The coating thickness is about 15 microns, with cBN (0-2 μm) and the volumetric ratio of about 42-47%. The substrates are standard WC-Co.

Tool 3: Solid PCBN tool insert (BSNG 432 series: 8100 from Diamond Innovations)

Workpiece: Hardened AISI 4340 steel with approximately 52 HRC.

In this study, two cutting speeds (m/s), three feeds (mm/rev), and a specific depth of cut (mm), are used. The cutting conditions are summarized in Table 1.

Table 1. Cutting conditions.

Cutting Conditions	Cutting Parameters		
	Speed (m/s)	Feed (mm/rev)	Depth of cut (mm)
1	1.778	0.013	0.254
2	1.778	0.051	0.254
3	1.778	0.102	0.254
4	3.048	0.013	0.254
5	3.048	0.051	0.254
6	3.048	0.102	0.254

For each cutting conditions, three repeated cuts were performed. At each time period for each cut, the flank wear were measure for three times. An optical microscope was used for measuring flank wear land on the cutting tool. Then, flank wear versus time for all six cutting conditions of the solid PCBN tool and the two types of coated composite tools were plotted. By observing the flank wear progress in the first 3 minutes of solid PCBN and of coated composite tool, a cutting condition that provided the smallest discrepancies between flank wear level of the coated composite tool and the solid PCBN was selected. In general, there are three wear stages of a cutting tool (DeGarmo, et al., 2007). The first stage where the wear rate of a cutting tool is high, usually takes few minutes and then the tool gradually reaches a secondary stage where the tool experiences a slow wear rate, and then the wear rate will increase rapidly again at the final stage of tool wear. By comparing the wear rate of solid PCBN and coated composite tool in the first few minutes, it could determine an approximated overall wear performance of the tools and save the material costs.

It has been found that at the feed of 0.102 mm/rev (0.0040 in/rev), the speed of 1.778 m/s (350 feet/min) and the depth of cut of 0.254 mm (0.01 in), the differences of the flank wear at each time period obtained from the solid PCBN and the coated composite tool were minimum. After a selected cutting condition was determined, that cutting condition was used for tool life comparisons between solid PCBN tool and the two types of coated composite tools. In this paper, the tool life criterion for each type of the cutting tool is at the flank

wear level of 0.381 mm (0.015 in).

After machining, the two types of coated composite tools were cut and SEM was used for taking pictures of the cross sectional areas of coated layers on the flank wear area of the tool. Energy Disperse Spectroscopy (EDS) system on the SEM was used to distinguish types of particles in the SEM pictures. It is found that the black dots are cBN particles, the dark gray areas are TiN where the light-gray area underneath is the substrate WC, as seen in Fig. 2 and Fig. 3.

Regression analysis was performed for demonstrating a mean of obtaining a tool life model as a function of cutting speed and feed. In general, a regression model is suitable for predicted the value of tool life in the range of the experimental setup. In this case, the cutting speed is from 1.778-3.048 m/s (350-600 feet/min), the feed is from 0.013-0.102 mm/rev (0.0005-0.0040 in/rev), with the depth of cut of 0.254 mm (0.01 in). Now, the tool life model has been developed. The tool life (T) is derived from two factors; speed (V) and feed (f) where C is a constant. Equation (1) shows the general equation of the tool life model.

$$T = CV^x f^y \qquad\qquad (1)$$

By taking log for all of the terms in (1), now it becomes,

$$\log T = \log C + x\ \log V + y\ \log f \qquad\qquad (2)$$

From (2), x, y and C can be obtained by using regression analysis tool in the Microsoft Excel or other statistical software such as MINITAB.

RESULTS

Average flank wear results for solid PCBN tool, coated composite tool with cBN particle size <0.5 μm and coated composite tool with cBN particle size < 2 μm are shown in Table 2. Fig. 1 shows a plot of the average flank wear for the three types of cutting tools against the time. Fig. 2 and Fig. 3 shows cross sectional area of coated layer at the flank location after machining for coated composite tools with cBN particle size <0.5 μm and <2 μm, respectively. Table 3 shows coefficients x, y and C obtained from the regression analysis for coated composite tool with cBN particle size <0.5 μm.

Table 2. Average Flank Wear Results.

Time (min)	Average Flank Wear (mm)		
	PCBN Tool	**Tool 1 (smaller cBN)**	**Tool 2 (larger cBN)**
0.2	0	0.05588	0.05588
1.1	0.00254	0.0762	0.05588
1.9	0.02794	0.09398	0.05994
2.4	0.03302	0.09906	0.06553
18.2	0.1397	0.19812	0.2794
24.9	0.18542	0.2286	0.37846
27.7	0.21844	0.2413	
48	0.36068	0.36322	
50.2	0.37592	0.38354	
51	0.37846		
52	0.38354		

Table 3. Regression analysis result for tool life.

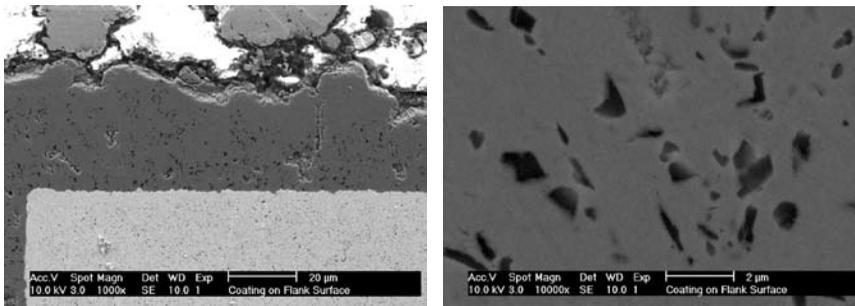| Tool	C	x	y
cBN<0.5 μm	106.85	-4.01	-2.04
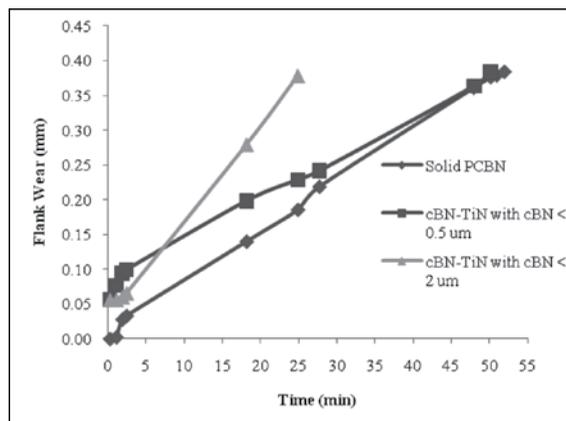
Figure 1. Flank wear (feed 0.102 mm/rev, cutting speed 1.778 m/s, depth of cut 0.254 mm).
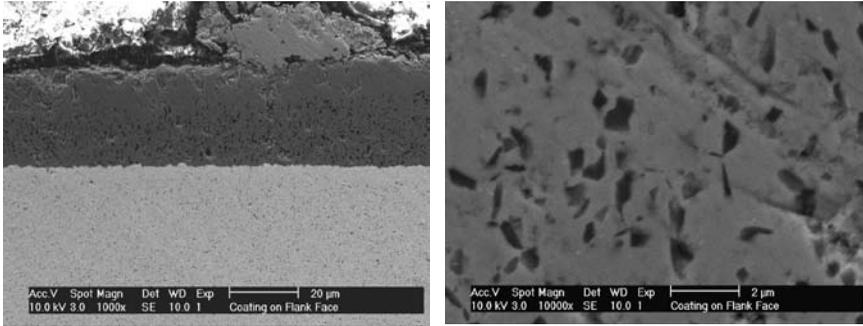
Figure 2. Coating cross section at flank area of coated cBN-TiN composite tool (cBN< 0.5 µm).

Figure 3. Coating cross section at flank area of coated cBN-TiN composite tool (cBN< 2 µm).

DISCUSSION

At the flank wear of about 0.381 mm (0.015 in), the coated composite tool with cBN particle size <0.5 µm took about 50 minutes to reach this flank wear level. The solid PCBN tools took about 52 minutes while it took about 25 minutes for the coated composite tool with cBN <2 µm to reach the same level of the flank wear. It can be seen that the wear rate of the coated composite tool with cBN particle < 2 µm is about 2 times of the solid PCBN tool. However, for coated composite tool with cBN < 0.5 µm, the tool has a comparable wear rate as the solid PCBN. It is believed that coating with fine cBN particles produced better tool life is due to: (1) the high strength (hardness) associated with the particles with reduced size, leading to high wear resistance. According to Hall-Petch relationship, the strength of the materials increases as particle or grain size deceases till 10 nm; (2) high surface area related to the small particles, contributing to better adhesion and less chance of particle pull-out, if there is any; (3) potential high particle density for the fine cBN, if the degree of agglomeration is the same as cBN of less than 2 µm.

Fig. 2 and Fig. 3 show SEM pictures of the cross sectional area for coated composite cutting tools used in this experiment on the flank wear locations.

These SEM pictures were taken at the magnification of 1,000 and 10,000. The black dots are cBN particles and it is worth to note that the majority of these cBN particles were not pulled out after machining.

At the same powder mass deposited, cBN particles with size less than 0.5 µm produced more uniform coating as seen in Fig. 2 and Fig. 3. The apparent particle density in the coating is higher due to high ratio of q/m for the cBN with relatively small size. The distribution of the particles is more uniform. Occasional particle clusters have been observed in the cross-sections of both cases. The SEM pictures (Fig. 2-3) also show a support of the coating technique that the cBN particles still adhere to the surface after a period of machining time and these cBN particles also spread randomly throughout the coated layer of the cutting tools.

According to results in Table 3, the tool life equation for the coated composite tool is shown in (3).

$$T = 10^{6.85} * V^{-4.01} * f^{-2.04} \tag{3}$$

For (3), the unit of cutting speed is feet/min, and the unit for the feed is in/rev. This equation will be helpful for determining an approximated tool life of the composite cBN-TiN coated on WC tool.

CONCLUSION

The results show that a coated cutting tool with a smaller coated cBN particle size has a comparative tool life as solid Polycrystalline Boron Nitride (PCBN) tool which is a dominant tool in hard turning applications and a tool life twice as long as a coated tool with larger cBN particle size. The cost of manufacture a coated composite cutting tool is about $7.50 compared to the cost of $104 of a solid PCBN cutting tool. This shows a significant impact on cost benefit for manufacturing of hard materials.

Microstructures of coated layers for the tool with smaller cBN particle size at the flank location show a more uniform coating than the coated tool with larger cBN size. The more uniformity of the coating could contribute to a longer tool life of a coating with smaller cBN particle. It can be seen that the majority of cBN particles are still attached to the substrate throughout the life of the tool for both types of coated composite tools. This would support the validity of the coating techniques.

The tool life model is useful for manufacturers in their planning and improving their process efficiency. A regression analysis model for the tool life of coated composite tools with cBN particle size less than 0.5 µm was constructed as a demonstration for a mean to predict a tool life of cutting tool in metal cutting. The approach can be used for obtaining tool life model of cutting tool with other coated particle sizes or cutting parameters.

REFERENCES

Abrao, A.M., and Aspinwall, D.K. 1996. The surface integrity of turned and ground hardened bearing steel. Wear, 196: 279-284.

Agha, S.R., and Liu, C.R. 2000. Experimental Study on the Performance of superfinish Hard Turned Surfaces in Rolling Contact. Wear, 244: 52-59.

Bossom, P.K. 1990. Finish Machining of Hard Ferrous Workpieces. Industrial Diamond Review, May: 228-232.

Chou, Y.K., and Evans, C.J. 1999. Cubic born nitride tool wear in interrupted hard cutting. Wear, 229: 234-245.

DeGarmo, E.P., Black, J.T., and Kohser, R.A. 2007. DeGarmo's Material and Processes in Manufacturing, 10th edition, John Wiley & Son Inc., Hoboken, NJ, 2007.

Halpin, T., Byrne, G., and Barry, J. 2005. The performance of PCBN in hard turning. Industrial Diamond Review, 65(4): 52-54+56-60.

Konig, W., Berktold, A., and Koch, K.F. 1993. Turning versus grinding–A comparison of surface integrity aspects and attainable accuracies. Ann CIRP, 42: 39-43.

Liu, C.R., and Mittal, S. 1995. Single step super-finishing using hard turning resulting in superior surface integrity. Journal of Manufacturing Systems, 14: 124-133.

Jochmann, S. and Wirtz, H. 1999. Achieving Precision Grinding by Hard Turning. ASME, 10: 817-823.

Liu, C.R., and Mittal, S. 1996. Single step super-finish hard machining: feasibility and feasible cutting conditions. Robotics and Computer Integrated Manufacturing Systems, 12(1):15-24.

Liu, C.R., and Mittal, S. 1998. Optimal Pre-stressing the Surface of a Component by Superfinish Hard Turning for Maximum Fatigue Life in Rolling Contact. Wear, 219: 128-140.

Russell, W.C., Malshe, A.P., Yedave, S.N., and Brown, W.D. 2003. CBN-TiN composite coating using a novel combinatorial method - Structure and performance in metal cutting. Journal of Manufacturing Science and Engineering, Transactions of the ASME, 125(3): 431-435.

Tamizharasan, T., Selvaraj, T., and Noorul Haq, A. 2006. Analysis of tool wear and surface finish in hard turning. International Journal of Advanced Manufacturing Technology, 28(7-8): 671-679.

Wick, C. 1988. Machining with PCBN Tools. Manufacturing Engineering, July: 73-78.