MACHINING HARDENED STEEL
WITH CERAMIC-COATED AND UNCOATED CBN CUTTING TOOLS

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ABSTRACT

As part of a continuing study of tool wear in hard turning, five different cutting tool materials were selected for full tool life tests at a range of reasonable cutting conditions. The tools were ceramic-coated and uncoated polycrystalline cubic boron nitride (CBN). Previous results have indicated that low CBN content tools perform better than high CBN content tools. The low CBN content tools have a moderate CBN percentage combined with ceramic binder materials and are designed for finish machining of hardened steels, making these tools the focus of this study. Additionally, new low CBN content tools that have TiN and TiAlN coatings were tested. The coatings are advertised to insulate the CBN substrate and improve tool life, which held true for most conditions, although significant chipping was initially observed on the crater scars of these tools. A new tool geometry design was also tested, which had a wiper on the nose radius of the tool that allowed improved surface finish without sacrificing productivity or tool life substantially.

INTRODUCTION

Recent improvements in machine tool rigidity and the development of ceramic and CBN cutting tools have allowed the machining of hardened steel to replace many grinding operations due to the numerous advantages of hard turning. Even though small depths of cut and feed rates are required for hard turning, material removal rates in hard turning can be much higher than grinding (Tonshoff, et al. 1996). It has been estimated that resulting reduction in machining time could be as high as 60% (Tonshoff, et al. 1995). A reduction in the number of required machine tools may also be observed as a result of the increased flexibility of the turning process as compared to grinding (Konig, et al. 1984; Tonshoff, et al. 1996). The possibility of eliminating cutting coolant is another substantial economic and environmental advantage of hard turning.

It seems obvious that hard turning is an attractive replacement for many grinding operations, but implementation in industry remains relatively low, particularly for critical surfaces. Two particular concerns are the cost of expensive tool materials, and the effect of the process on surface integrity. Hard turning can influence the workpiece surface microstructure by generating undesirable residual stress patterns and over hardened surface zones that are referred to as “white layers” (Konig, et al. 1993; Shaw 1993; Tonshoff, et al. 1995; Brinksmeier, et al. 1999; Griffiths 1987). The cause and effect of these residual stress patterns and white layer generation are not fully understood. White layer and residual tensile stresses are expected to reduce fatigue life, but research comparing the fatigue lives of hard turned and ground surfaces found the hard turned surfaces to have increased lives despite the existence of brittle white layers (Abrao and

Aspinwall 1996). In some cases, compressive stresses have been found on hard turned surfaces that improved fatigue life (Thiele and Melkote 1999, Liu and Mittal 1998). Because the effects of white layer on the resulting component performance are not well understood, industry remains reluctant to produce critical surfaces by a hard turning process that may contain undesirable conditions.

Cutting tools required for hard turning are relatively expensive, so it is also important to investigate tool life to assure the economic justification for hard turning. Regardless of the attainable dimensional accuracy and surface quality, hard turning will not replace grinding operations if the cost is too high. Poor selection of cutting conditions can lead to excessive tool wear and eliminate any cost savings, while conservative conditions may also increase cost by reducing productivity. Selection of optimal cutting conditions must balance the tradeoff between productivity and tool life, thus the need to study effects of cutting conditions on the wear behavior of different hard turning tool materials.

EXPERIMENTAL CONDITIONS

Nineteen full tool life tests were run with uncoated and ceramic-coated CBN cutting tools. Table 1 lists the test conditions and tool materials. Cutting speeds and feed rates were selected to span the range of conditions recommended by the tool suppliers. A high and low value of cutting speed and feed were selected, while cutting depth was held constant at a reasonable value for all tests. Based on feedback from manufacturers, cutting depth is usually not considered a variable process parameter, because it is typically defined by the amount of stock that must be removed. Thus, only speed and feed were varied. A combination of an intermediate speed and feed was also run with the coated CBN inserts, and was replicated to test the repeatability of tool failures.

Five different grades of CBN tools were evaluated. The tools were provided by two different manufacturers, labeled ‘A’ and ‘B’ so that neither is endorsed. The uncoated tools were typical low CBN content tools. These tools are considered competing grades of CBN tools, although there are certainly small differences in composition and processing. While the manufacturers would not provide detailed processing information, the composition of both low CBN content tools had a moderate CBN percentage (~65%) combined with ceramic binder materials. These tools are designed for finish machining of hardened steels. Higher CBN content tools (~90%) typically have metallic binders, and their improved fracture toughness makes them better suited for interrupted cuts and large cutting depths (which was not the case for this study).

Coated versions of CBN tools were also obtained from each supplier. The tools used for conditions 4 through 8 in Table 1 had TiAlN coatings on top of a low CBN content substrate. For conditions 12 through 16, tools with TiN coatings on a low CBN content substrate were tested.

The last tests used uncoated low CBN content tools that had a special wiper geometry on the cutting edge. The wiper geometry allowed improved surface finish without sacrificing lower feeds.

TABLE 1. EXPERIMENTAL CUTTING CONDITIONS

Condition	Speed (m/min)	Feed (mm/rev)	Depth (mm)	Tool Material
1	183	0.152	0.203	'A' Uncoated
2	183	0.076	0.203	
3	91	0.152	0.203	
4	183	0.152	0.203	'A' TiAlN Coated
5	183	0.076	0.203	
6	91	0.152	0.203	
7	137	0.114	0.203	
8	137	0.114	0.203	
9	183	0.152	0.203	'B' Uncoated
10	183	0.076	0.203	
11	91	0.152	0.203	
12	183	0.152	0.203	'B' TiN Coated
13	183	0.076	0.203	
14	91	0.152	0.203	
15	137	0.114	0.203	
16	137	0.114	0.203	
17	183	0.152	0.203	'B' Uncoated Wiper
18	183	0.076	0.203	
19	91	0.152	0.203	

All cutting inserts were an 80˚ diamond shape that had a 0.8 mm nose radius and a 20˚-25˚ cutting edge chamfer that was 0.1 mm wide. The toolholder provided a -5˚ side and back rake angle. Workpiece material was AISI 52100 tube stock hardened to approximately 62 HRC. This hardness was maintained throughout the thickness of the tube, as it was possible to quench from both the outer and inner diameter. Because a uniform hardness was achievable, it was decided to face the bars for testing so that no scrap material would remain, as would occur if turning tests were performed. Another disadvantage of turning was found in previous testing, when chatter occurred when the wall thickness of the tube stock dropped below a critical value dependent on the test condition. Chatter tended to lead to premature tool failure, so facing had the advantage of eliminating this concern.

CRATER WEAR

Figure 1 through Figure 3 show optical micrographs of cutting tools at different stages during each tool's life. The top image in each figure shows the tool after very little cutting has taken place, the middle image shows each tool at an intermediate stage, and the bottom image shows the tool just prior to failure. The tools in all three figures were used at a cutting speed of 91 m/min and a feed of 0.152 mm/rev, which was the condition that resulted in best tool life and allowed more frequent tool inspections. Good photographs of the coated tools were difficult to obtain at this magnification, so the best tool images were selected—which unfortunately occurred at different time intervals.

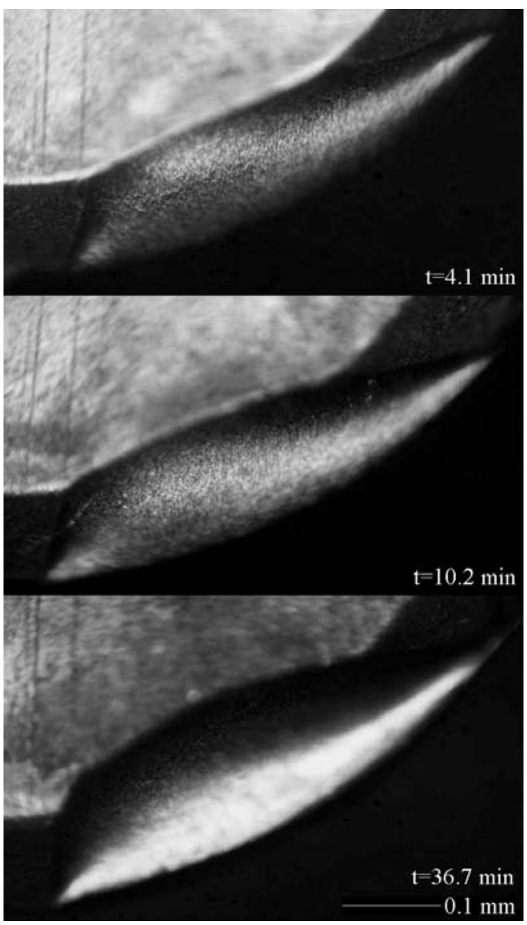

FIGURE 1. C11 CRATER PROGRESSION

Figure 1 shows the progression of crater wear on a low CBN content tool. This type of wear progression was typical for uncoated low CBN content tools from both manufacturers. In the top image in the figure, the crater began to form at the region of the tool that contacts the workpiece. This region was defined by the cutting depth and the feed rate, and occurred almost exclusively along the edge chamfer. The bottom two images show that the crater grew progressively larger and deeper as cutting continued. Although it is difficult to recognize from the optical micrograph, the bottom edge of the cutting tool sharpened with increased crater wear. The initial edge chamfer was provided to strengthen the edge of the brittle cutting tool. As crater wear progressed, the strong initial negative rake geometry of the chamfer changed into a weak, sharp edge with a positive rake. This geometry change led to weakening of all cutting tools, which will be discussed in the following section.

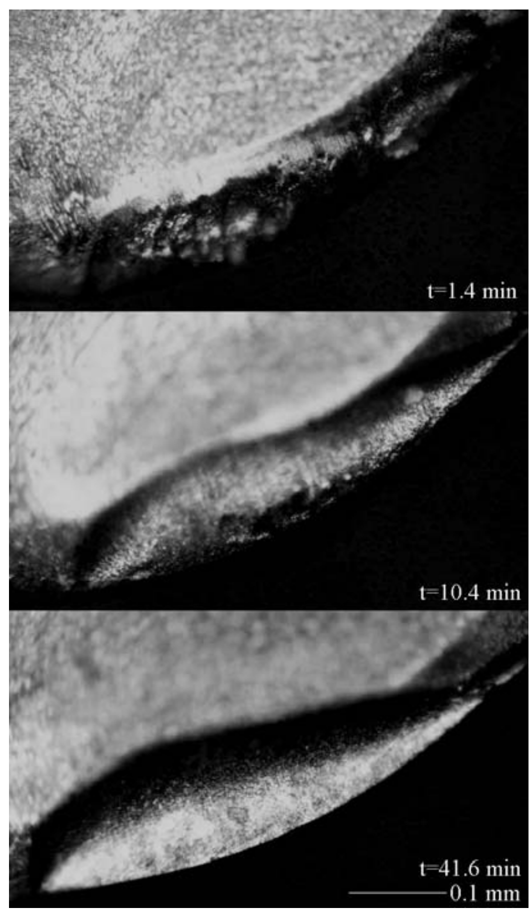

FIGURE 2. C6 CRATER PROGRESSION

The uncoated tools from both manufacturers formed smooth crater and flank surfaces with no noticeable chipping. The ceramic-coated CBN tools did not form smooth surfaces initially, showing significant chipping until the coated surface was worn away down to the CBN substrate. Once the coated surfaces were worn away in the crater region, further progression of wear was very similar to wear of the uncoated tools. Chipping of the ceramic coating occurred almost immediately after cutting began, as can be seen in Figure 2 and Figure 3. There was no distinct change in flank wear rate as the coating was worn away, but crater formation did increase once the coating was gone.

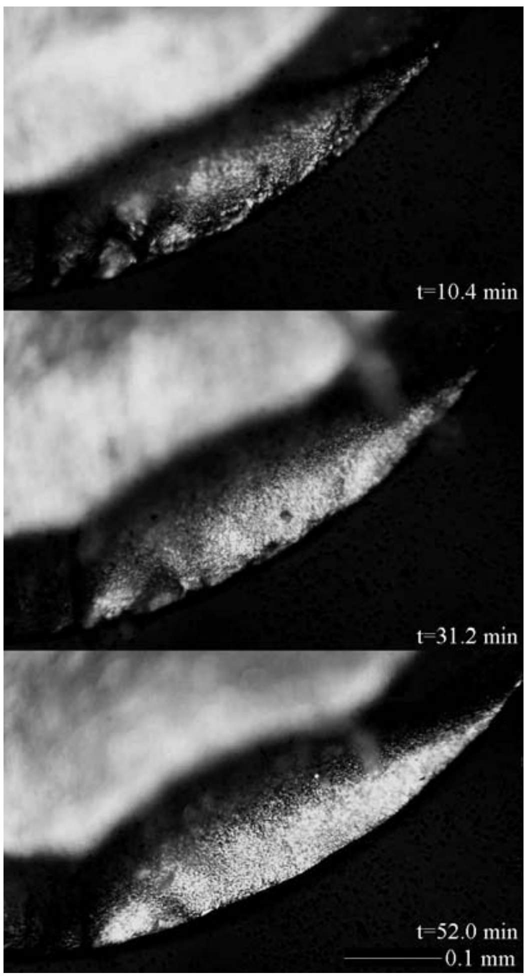

FIGURE 3. C14 CRATER PROGRESSION

The increased occurrence of chipping in the ceramic coating was not altogether surprising. CBN has higher fracture toughness than most ceramics, and thus should be able to withstand loading without fracture better than the ceramic coatings. The advantage of the coating appears to be that they provided a 'break away' layer that endured some cutting and allowed increased tool life by delaying the exposure and wear of the CBN substrate.

TOOL FAILURE

While optical micrographs allow observation of edge chipping, they do not provide significant information about changes in the nominal cutting edge geometry. Using a Zygo New View 200 microscope, three-dimensional images of cutting tools were obtained. This microscope uses white light interferometry to obtain the three-dimensional topography of the tool surface. The progression of crater wear measured for an uncoated tool can be seen in Figure 4. Images such as Figure 4 are not detailed enough to observe the chipping that occurred in the coated layers, but they allow changes in the nominal geometry to be seen. As the crater formed, the negative geometry that existed from the edge chamfer changed into a sharp positive geometry at the tip of the cutting edge. This change in edge geometry weakened the cutting tool and ultimately led to tool failure by fracture at the weak point of the edge.

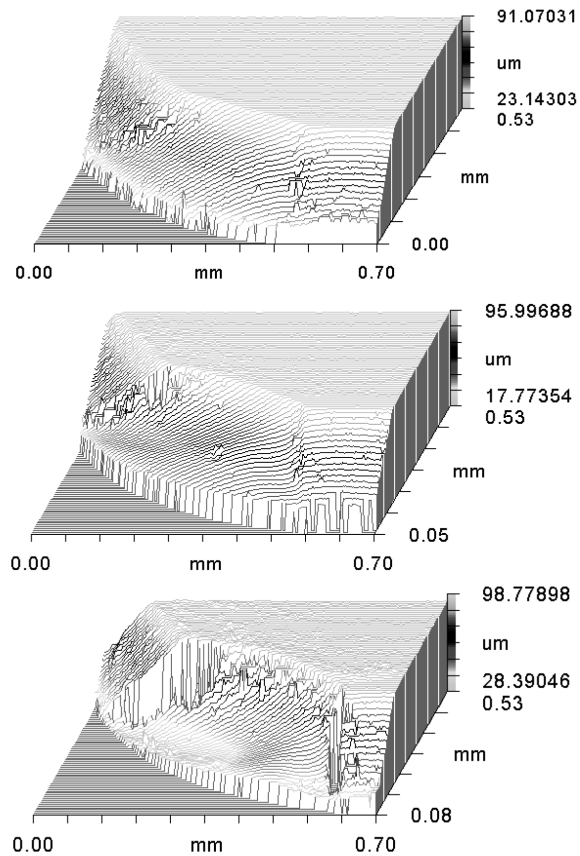

FIGURE 4. C3 ZYGO MEASURED CRATER

A typical tool failure can be seen in Figure 5. All tools failed by a similar fracture at the weak cutting edge that resulted from crater wear. The profile of this tool just prior to failure can be seen in Figure 6. The two-dimensional profile of the crater reveals the weak portion of the cutting edge, where there was a transition at the bottom of the profile from a negative to positive effective rake. All tools showed a similar geometry shortly before failure.

FIGURE 5. C6 FAILURE

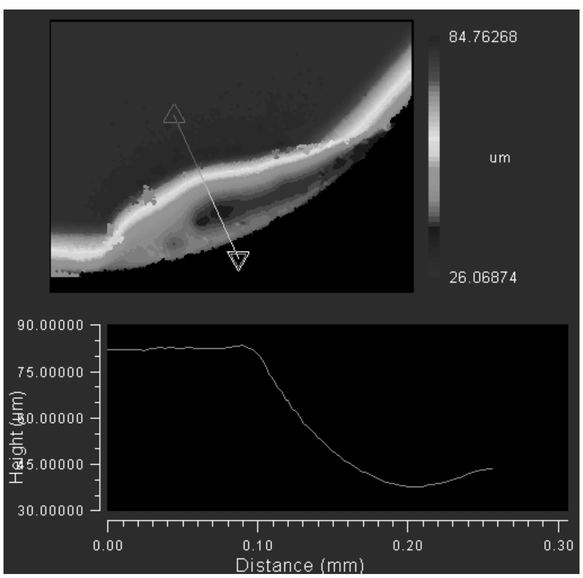

FIGURE 6. C6 PROFILE BEFORE FAILURE

TOOL LIFE

Because all tools failed as a result of a fracture at the cutting edge, it was decided not to define an arbitrary flank land size that constituted the end of a tool's useful life. It was found that most tools had a maximum flank land measurement between 0.15 and 0.2 mm at the time edge failure occurred, but the flank land was not used to define tool life.

TABLE 2. TOOL LIFE RESULTS

Condition	Speed (m/min)	Feed (mm/rev)	Tool life (min)	Volume (cm^3)	MRR (cm^3/min)
1	183	0.152	4.0	23	5.66
2	183	0.076	6.8	19	2.83
3	91	0.152	27.8	79	2.83
4	183	0.152	3.6	21	5.66
5	183	0.076	7.3	21	2.83
6	91	0.152	62.4	177	2.83
7	137	0.114	15.0	48	3.19
8	137	0.114	18.5	59	3.19
9	183	0.152	7.6	43	5.66
10	183	0.076	10.2	29	2.83
11	91	0.152	44.9	127	2.83
12	183	0.152	7.8	44	5.66
13	183	0.076	8.6	24	2.83
14	91	0.152	49.7	141	2.83
15	137	0.114	13.9	44	3.19
16	137	0.114	13.9	44	3.19
17	183	0.152	7.2	41	5.66
18	183	0.076	6.2	18	2.83
19	91	0.152	39.0	111	2.83

Table 2 contains the experimental tool life results from each of the tools and conditions tested. Two measurements of tool performance are included in the table: the cumulative cutting time, and the cumulative volume of material removed by the tool. The results indicate (as expected) that cutting speed affected tool life much more significantly than feed rate affected tool life. Decreased cutting speed resulted in significant improvements in the cumulative cutting time and removed volume for all tools. Decreased feed rates gave a smaller increase in cutting time, but still an improvement. However, looking at tool performance measured by the volume of material removed before tool failure shows a different effect. Using this metric, a decrease in feed actually worsened the performance of each tool. For most applications, this is a more sensible metric to use for selection of cutting conditions, because it relates directly to the number of parts that could be machined with each cutting edge. Dividing the cumulative volume before tool failure by the volume of material removed per part gives the number of parts that could be machined. Cutting time is more ambiguous because the number of parts must be calculated from cutting time and the cutting conditions, as shown in (1), where n is the number of parts, f is the feed, v is the cutting speed, d is the cutting depth, T is the cumulative cutting time, and V_{part} is the volume removed from each part.

$$n = \frac{f \cdot v \cdot d \cdot T}{V_{part}} \qquad (1)$$

To enable selection of optimal conditions, it is desired to understand the tradeoffs between tool life, volume removed, and material removal rate. Table 2 shows that the condition that was best for one of the three was not necessarily the best for the other two. The 'best' condition may vary considerably, depending on the costs associated with tools, machines, operators, and setup times, all of which may be very different between manufacturers. To optimize the cutting conditions based on cost considerations, the effect on tool life is very important because CBN tools are relatively expensive. For this purpose, an empirical Taylor type tool life equation (2) was used, where *T*, *v*, and *f* are tool life (min), cutting speed (m/min), and feed (mm).

$$T = k \cdot v^a f^b \qquad (2)$$

Experimental data were used to obtain the constants in (2) by modifying the equation and using linear regression.

$$\ln T = \ln k + a \ln v + b \ln f \qquad (3)$$

The form of (3) is identical to (4) if the variables are defined appropriately.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 \qquad (4)$$

The error between experimental tool life and the model prediction of tool life can be defined by (5).

$$[\varepsilon] = [y] - [x][\beta] \qquad (5)$$

Minimizing the sum of the squared error allows calculation of the constants contained in β.

$$[\beta] = \left[[x]^T [x]\right]^{-1} [x]^T [y] \qquad (6)$$

Experimental data for *y* (ln *T*) and *x* (ln *v* and ln *f*) were used in (6) to calculate the empirical constants *a* and *b* for each tool, as listed in Table 3. When a tool was used at only three conditions, the three empirical constants were calculated directly from the data, and the error appears to be zero since each data point was used for the calculation. For the coated tools, which were also used at an intermediate speed and feed (and replicated), the regression results show tool life numbers that are within 14% of experimental results.

The results indicate that the effect of cutting speed on tool life was similar for most tools, with *a* having a value near –2.5. The TiAlN coated tool seemed to have a greater sensitivity to cutting speed. The effect of feed on tool life was much smaller, and appears to vary significantly between tools. However, closer values of *b* might be expected if more experimental data were available for each tool to calculate the empirical constants.

TABLE 3. TAYLOR CONSTANTS AND PREDICTIONS

Condition	Tool life (min)	Taylor Contants T=k(V)^a*(f)^b		Prediction (min)
1	4.0	k =	2.02E+06	4.0
2	6.8	a =	-2.79	6.8
3	27.8	b =	-0.75	27.8
4	3.6			3.7
5	7.3	k =	1.14E+09	7.5
6	62.4	a =	-4.12	64.1
7	15.0	b =	-1.02	16.2
8	18.5			16.2
9	7.6	k =	2.13E+06	7.6
10	10.2	a =	-2.56	10.2
11	44.9	b =	-0.42	44.9
12	7.8			7.5
13	8.6	k =	4.67E+06	7.7
14	49.7	a =	-2.58	44.5
15	13.9	b =	-0.04	15.9
16	13.9			15.9
17	7.2	k =	3.56E+06	7.2
18	6.2	a =	-2.45	6.2
19	39.0	b =	0.20	39.0

SUMMARY

Full tool life experiments were performed on five different cutting tool materials at a range of cutting conditions. Low CBN content tools, TiN and TiAlN ceramic-coated CBN tools, and a wiper geometry tool were all tested at a range of conditions recommended by the tool suppliers.

Tool wear was monitored during the life of each tool by using an optical microscope and white light interferometry to observe wear scars on the crater and flank surfaces. Smooth crater surfaces were formed on the low CBN content tools, which wore progressively until a weak cutting edge geometry was formed and tool fracture occurred. Both the TiN and TiAlN coated tools showed significant chipping of the coated layer. Once the coating had been worn away, smooth crater surfaces formed in the CBN substrate, similar to wear of the uncoated tools. The uncoated wiper geometry tools behaved very similar to the uncoated tools from the same supplier, except that tool life was shorter at each condition.

Selection of optimal cutting parameters must balance the tradeoff between productivity and tool life. In general, conditions that tend to improve productivity also tend to shorten tool life. To understand the effect of cutting conditions on tool life, an empirical Taylor type model was used. The empirical constants from the equation were obtained from experimental data using linear regression. Life predictions from the model match experimental result within 14%, indicating that the model does an adequate job of capturing the effect of cutting speed and feed on tool life.

The experimental results presented here are part of a study of the effect of process conditions on the wear behavior of different CBN tools. Several tools are being used for a more extensive tool wear study to expose the materials to a broader set of test conditions. The goal of this work is to optimize process parameters in order to minimize costs associated with the hard turning process. As mentioned, a tradeoff exists between productivity and tool life, and improved surface finish also conflicts with removal rate. Experimental work will lead to the development of models of wear behavior and tool life, providing manufacturers tools for making decisions about process conditions.

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