

# **WEAR TRENDS OF PCBN CUTTING TOOLS IN HARD TURNING**

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## **1. ABSTRACT**

Hard turning is a developing technology that offers many potential benefits compared to grinding, which remains the standard finishing process for critical hardened steel surfaces. To increase the implementation of this technology, questions about the ability of this process to produce surfaces that meet surface finish and integrity requirements must be answered. Additionally, the economics of the process must be justified, which requires a better understanding of tool wear patterns and life predictions. An ongoing comparative study of wear rates and tool lives under varying cutting parameters is presented here. To date, the study has consisted of seventeen different machining conditions with four different cutting tool materials. Tool life results agree with previous research in this area, indicating that polycrystalline cubic boron nitride (PCBN) tools with low CBN content have improved lives resulting from the benefits of the ceramic binders compared to the cobalt binder typically used for higher CBN content tools. More interesting is a resulting trend in flank wear patterns that could currently help to predict tool life under certain cutting conditions. Further work is being done to understand the wear process in an attempt to model this relationship for a larger range of conditions.

## **2. BACKGROUND**

The potential economic benefits of hard turning can be offset by rapid tool wear or premature tool failure if the brittle cutting tools required for hard turning are not used properly. Even steady, progressive tool wear can result in significant changes in cutting forces, residual stresses, and microstructural changes in the form of a rehardened surface layer (often referred to as white layer). Research in this area has often focused on the

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choice of appropriate cutting tool materials, with results typically indicating that CBN tools perform better than carbides or alumina based tools (Konig et al. 1984, Konig et al. 1990, Abrao et al. 1995, Rigaut et al. 1993, Luo et al. 1999). Under proper conditions, CBN tooling can easily pay for its expensive initial cost with substantial tool life. However, short tool life is not the only result of rapid tool wear. Flank wear has been found to be the most significant factor affecting the depth of white layer (Chou and Barash 1995). Similar detrimental effects on residual stresses and white layers have been found by others (Konig et al. 1990, Tonshoff et al. 1995, Chou and Evans 1998, Abrao and Aspinwall 1996). Thus, even acceptable wear rates can lead to tools that produce unacceptable surface integrity. Without a better understanding of the wear behavior of CBN tools and the effects of worn tools on workpiece surface quality, implementation of hard turning will remain limited.

### 3. EXPERIMENTAL CONDITIONS

Hard turning was performed at each of the conditions listed in Table 1 for the entire life of seventeen different PCBN cutting inserts. The test matrix shows that four different PCBN grades were tested—a high and low CBN content from two different tool manufacturers. So that a particular tool manufacturer is not endorsed, they are referred to as A and B in this paper. The test conditions span the range of recommended values from the tool suppliers, and are comparable to cutting parameters in previous studies of hard turning (Abrao et al. 1995, Bossom 1990, Konig et al. 1984, Sood et al. 2000).

**Table 1.** Experimental cutting conditions

Test #	Speed (m/min)	Feed (mm/rev)	DOC (mm)	Speed (ft/min)	Feed (inch/rev)	DOC (inch)	Tool Material	Hardness (HRC)
1	183	0.152	0.203	600	0.006	0.008	'A' High CBN	58
2	183	0.076	0.203	600	0.003	0.008	'A' High CBN	58
3	91	0.152	0.203	300	0.006	0.008	'A' High CBN	58
4	91	0.152	0.203	300	0.006	0.008	'A' High CBN	58
5	183	0.152	0.203	600	0.006	0.008	'A' High CBN	62
6	183	0.152	0.508	600	0.006	0.020	'A' High CBN	58
7	183	0.076	0.508	600	0.003	0.020	'A' High CBN	62
8	91	0.152	0.508	300	0.006	0.020	'A' High CBN	62
9	183	0.152	0.203	600	0.006	0.008	'A' Low CBN	62
10	183	0.076	0.203	600	0.003	0.008	'A' Low CBN	62
11	91	0.152	0.203	300	0.006	0.008	'A' Low CBN	62
12	183	0.152	0.203	600	0.006	0.008	'B' High CBN	62
13	183	0.076	0.203	600	0.003	0.008	'B' High CBN	62
14	91	0.152	0.203	300	0.006	0.008	'B' High CBN	62
15	183	0.152	0.203	600	0.006	0.008	'B' Low CBN	62
16	183	0.076	0.203	600	0.003	0.008	'B' Low CBN	62
17	91	0.152	0.203	300	0.006	0.008	'B' Low CBN	62

A picture of the test setup can be seen in Figure 1. All machining was done on a Hardinge Conquest T-42 SP lathe, which has a 7.5 kW (10 hp) spindle and maximum spindle speed of 6000 rpm. The material was AISI 52100 steel, hardened to nominal

values of 58 or 62 HRC. The material hardened to 58 HRC was solid bar stock, but it was found that the hardness decreased to as low as 50 HRC when cut to smaller diameters. Thus it was decided to machine hardened tube stock, which allowed a heat treatment that provided consistent hardness at  $62\pm 2$  HRC. The cutting insert geometry was an  $80^\circ$  diamond shape with a  $20^\circ$  edge chamfer 0.1 mm wide. The toolholder provided negative  $5^\circ$  side and back rake angles, and  $5^\circ$  side cutting-edge and end cutting-edge angles. The test procedure consisted of twenty cuts 2.54 cm in length, each at a decreasing diameter. Once the twenty cuts were made, the 2.54 cm length was removed by wire EDM, and the test cuts began again at the outer diameter. The oxidized layer from heat treatment was removed with a mixed alumina cutting insert so that all test passes were made on a clean surface. Tool inspections were made at regular intervals with an optical microscope and Zygo New View 200 microscope, which uses white light interferometry to produce images of surface topography.

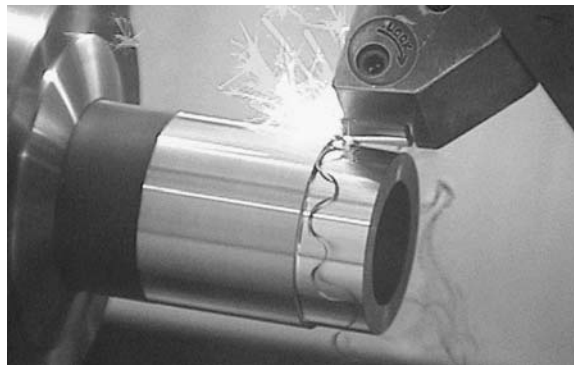


Figure 1. Test cut with PCBN tool

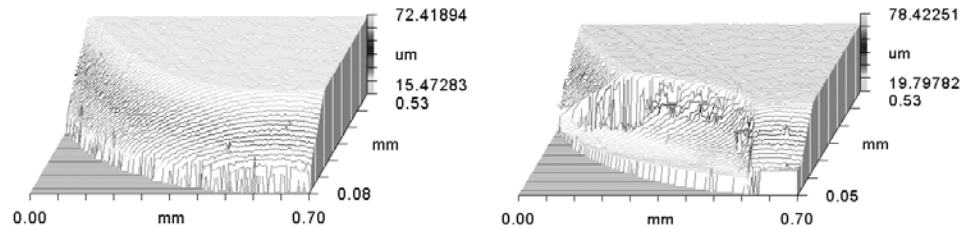
## 4. RESULTS

### 4.1 Crater Wear

It is well known that edge preparation is critical for acceptable tool life in hard turning. Due to the brittle nature of the materials used to machine hardened steel, strong edge geometries help to prevent premature tool failure or accelerated tool wear by edge chipping. The problem is magnified by the large cutting load and negative rake angles typically used for hard turning. Thus, tool manufacturers have developed the practice of preparing cutting edges with a honed radius or edge chamfer to strengthen the edge. These tools have shown improved tool life compared to unprepared (or up-sharp) tools.

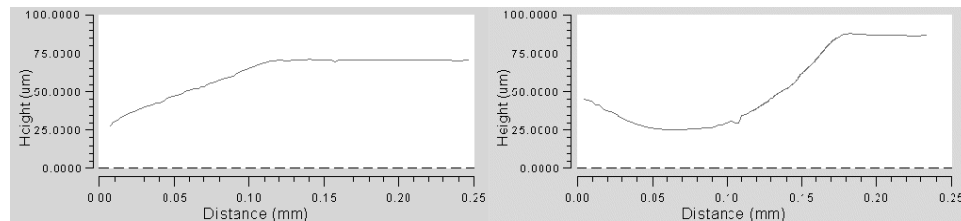
Previous work in hard turning has indicated that edge preparation affects cutting forces, residual stresses, and white layer generation in hard turning (Thiele et al. 2000, Jang et al. 1996, Liu and Barash 1982, Kishawy and Elbestawi 1998). This is not surprising, because the feed and depth of cut are small enough that cutting takes place on the nose radius of the cutting tool, and often occurs exclusively along the edge chamfer. This can be seen by the noticing the worn crater region in Figure 2. It is reasonable in

these cases to include the chamfer angle (often  $15^{\circ}$ - $25^{\circ}$ ) with the rake angle, making the rake as high as negative  $30^{\circ}$ . Even at larger feeds or depth of cut, the chamfer can cause a combination of rake angles between the chamfered edge and rake face of the tool. Knowing this, it is reasonable to argue that chamfered and honed tools are significantly different cutting tools, even though the geometry may be identical other than the edge preparation.



**Figure 2.** Cutting edge condition of new and worn tool at the nose radius

Because edge preparation is known to affect tool wear and the quality of machined surfaces, it is important to understand how the nominal cutting geometry changes over the life of the cutting tool. Figure 2 shows that the nominal cutting geometry exists for a short period of time. It is not enough to know what the tool edge looked like before cutting. Especially for the development of realistic finite element simulations of hard turning, changes in tool geometry over the life of the tool must be understood. While work is being done to develop three-dimensional modeling capabilities, the profile geometries seen in Figure 3 can provide improvements to existing two-dimensional simulations. The figure clearly shows the dramatic change in the cutting edge, and indicates the limitation of assuming nominal tool geometry.



**Figure 3.** Cutting edge profile of new and worn tool

Another interesting observation about Figure 3 is the change in effective rake angle. The rake angle of the cutting tool is often used in machining models or finite element simulations, but as already mentioned, large feeds or depth of cut can result in a combined rake angle between the chamfered or honed edge and rake face of the tool. Figure 3 shows an even more dramatic departure from standard tool geometry, as the rake angle varies from positive to a large negative value. The positive angle at the very tip of the cutting edge is weaker than the initial chamfered edge, and this is the region of the tool that fractured.

## 4.2 Flank Wear

While crater wear is important because it causes changes to the nominal cutting geometry, flank wear is the more typical method of quantifying the condition of a cutting tool. Figure 4 shows a new and worn cutting edge, where the flank land is clearly visible on the right side of the worn cutting edge. Measurement of the flank land was possible using images from a Zygo microscope, an optical microscope, and SEM. From Zygo data, two-dimensional profile sections (similar to Figure 3) can be obtained to easily measure the maximum width of the flank land.

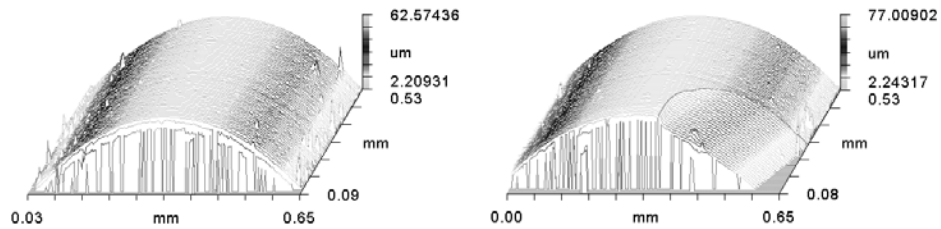


Figure 4. Flank land on a new and worn tool

Plotting the flank land measurements against the cutting time or the volume of material removed with the cutting tool shows a repeatable pattern in the wear data. Figures 5 and 6 show that for most cutting conditions, the flank wear initially proceeds rapidly, but then settles as the wear progresses. Equation (1) fits the data from each condition, where  $VB$  is the flank wear in  $\mu\text{m}$ ,  $t$  is the cumulative cutting time, and both  $a$  and  $b$  are constants particular to a combination of tool material and cutting condition.

$$VB = a(t)^b \quad (1)$$

The two figures show that most tools failed when the flank wear was between 150 and 200  $\mu\text{m}$ . Note that the data in the graphs represent the last measurements taken before tool failure, so the actual flank land at failure was larger than the last data point. While the cause of failure is ultimately a loading that causes a brittle fracture on some portion of the cutting edge, the repeatable flank land that corresponds to this condition may provide a simple method to predict failure. Knowing that failure is expected beyond a width of 150  $\mu\text{m}$ , Eq. (1) provides a method for calculating the cutting time (or amount of material or cutting length) that can be safely machined with a tool at different cutting conditions for which  $a$  and  $b$  are known. Further work is being done to determine how cutting parameters influence  $a$  and  $b$  in an attempt to develop a method for predicting flank wear for ranges of reasonable cutting conditions.

Comparison of the wear curves from the two different manufacturers shows that there are differences in the wear behavior between manufacturers. Even though they are marketed as comparable low or high CBN content tools, there can be substantial differences in the tool materials. For instance, the CBN itself can differ by processing conditions when transforming the BN from hexagonal to cubic form, grain size, shape, porosity, defects, inclusions, etc. Additionally, the binder materials can differ significantly. High CBN content tools are typically more than 90% CBN with a cobalt binder, while low CBN content tools are less than 70% CBN with TiC and/or TiN as the binder. While tools are generally lumped into one group or the other, manufacturers

often add small amounts of many other materials, which can make it difficult to find reasonably identical grades between manufacturers.

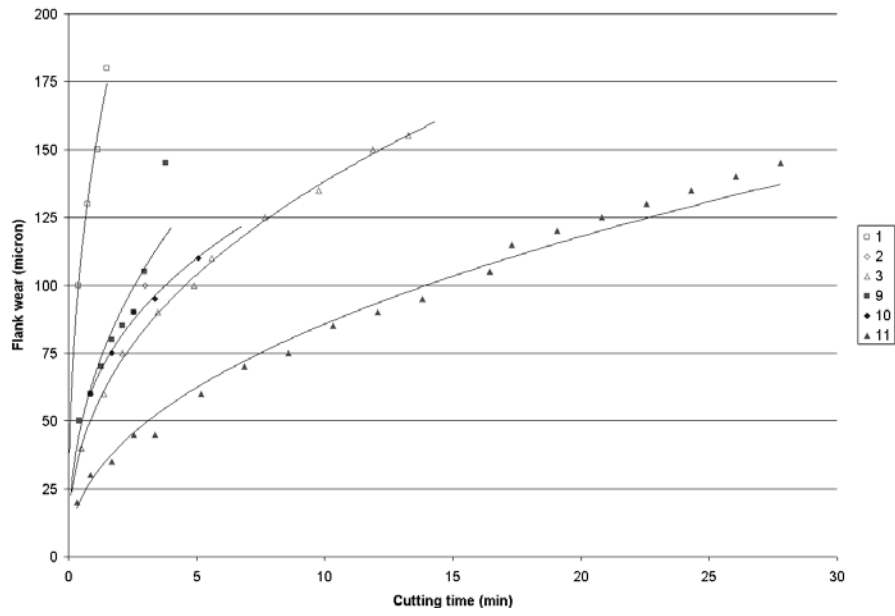


Figure 5. Flank wear for manufacturer 'A'

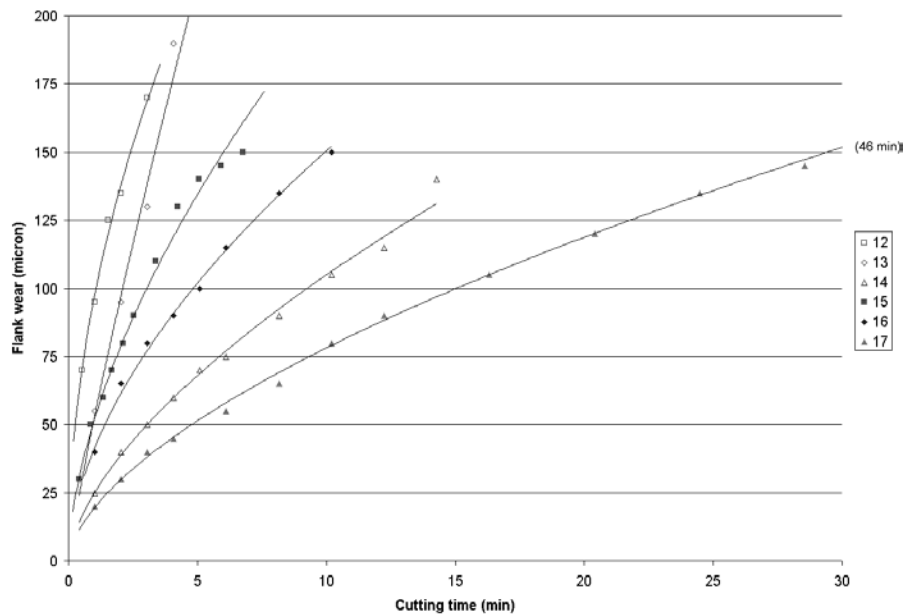


Figure 6. Flank wear for manufacturer 'B'

### 4.3 Tool Life

Figure 7 shows the tool life of each cutting condition listed in Table 1, measured by the amount of material removed with the tool. For all conditions, tool failure was determined at the time an edge fracture was noticed on the tool (100x), or when the flank wear exceeded 200  $\mu\text{m}$ . The 200  $\mu\text{m}$  condition was selected because most tools fractured with a flank land measurement between 150 and 200  $\mu\text{m}$ . It should be noted that the failure criteria was a noticeable edge fracture, but that many of the tools could have been used for more machining despite the edge fractures.

There were several noticeable trends in the tool life data shown in Figure 7. The most obvious observation is that tool life improved dramatically at conditions that had a cutting speed of 91.4 m/min instead of 182.9 m/min. This held true regardless of tool material, manufacturer, or depth of cut. However, further work is required to determine if an optimal cutting speed exists, as previous research has suggested (Abrao and Aspinwall 1996, Bossom 1990, Matsumoto and Narutaki 1996, Konig et al. 1984).

The effect of increased feed is more complicated. In terms of the volume of material removed with a tool (or cutting length), increased feed had a detrimental effect on tool life for the high content CBN tools from manufacturer A. This trend was reversed for the low CBN A tools and both grades of the B tools, where increased feed actually improved tool life by a small amount. However, Figure 8 shows that increased feed always reduced the cumulative cutting time at tool failure. Thus, for most of the CBN grades, increased feed reduced tool life in minutes, but actually increased the amount of material that could be removed by the tool. The later seems a more reasonable metric for tool life, as it relates directly to the number of parts that can be machined with the tool at a given depth of cut.

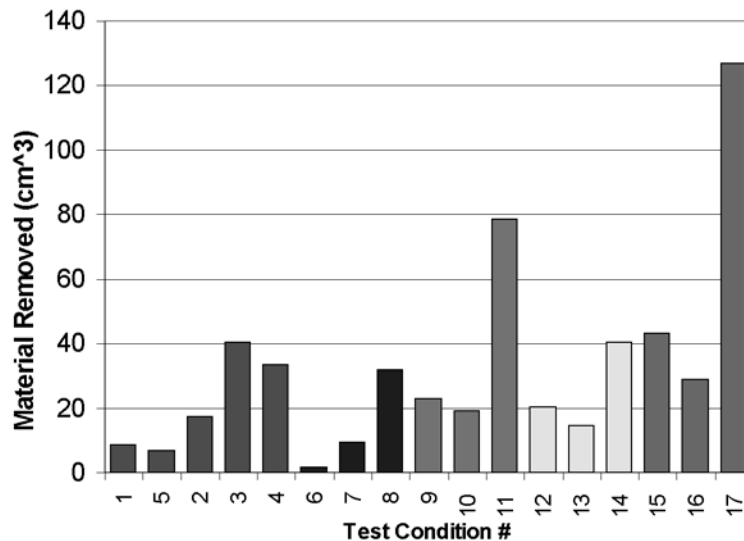
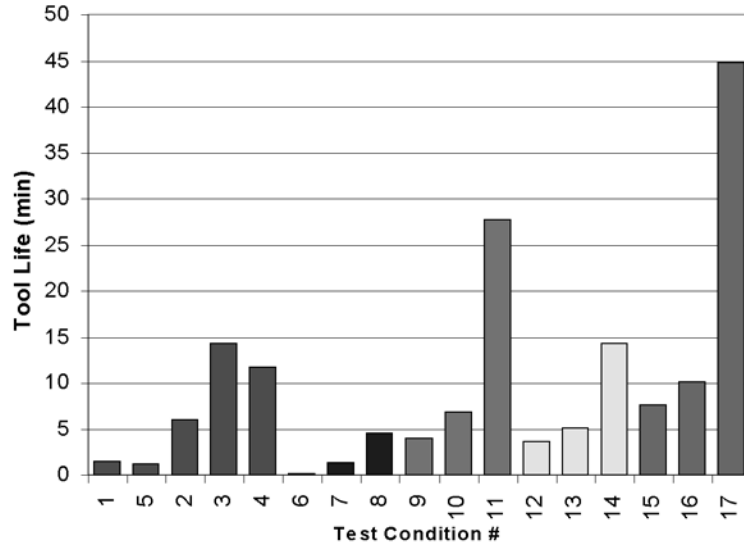


Figure 7. Tool life measured by amount of material removed by the tool



**Figure 8.** Tool life in minutes

The effect of cutting speed was more dominant than the effect of feed rate, which leads to the conclusion that for improved tool life, slower cutting speeds should generally be selected in combination with increased feed rates. Because material removal rate is linearly related to both feed rate and cutting speed, halving the cutting speed while doubling the feed rate maintains an equivalent removal rate. There are, however, limitations on acceptable feed rates—determined by the ability of the cutting tool to withstand increased cutting loads without fracture.

Figure 9 shows the similar tool life data as Figure 7, but it pairs high and low CBN content tools together by cutting conditions. This figure indicates the benefit of cutting with low CBN content tools. There are several arguments for the improved tool life of low CBN content tools. The increased bonding strength of the ceramic binder materials used in low CBN content tools may lead to increased tool life (Tonshoff et al. 1995). The ceramic binders also provide a composite tool material with a reduced thermal conductivity relative to high CBN content tools—in the range of 45 W/m-K compared to 100 W/m-K (Bossom 1990). If it is assumed that most of the heat generated by cutting (80-90%) is removed by the chip, the remaining heat must go into the workpiece or tool. The lower thermal conductivity reduces heat into the tool, which has the benefit of softening the workpiece and improving wear resistance of the tool by reducing the tool temperature (Narutaki et al. 1979). Additionally, there are indications that the chemical reactions may act preferentially to improve the lives of low CBN content tools (Barry and Byrne 2000).

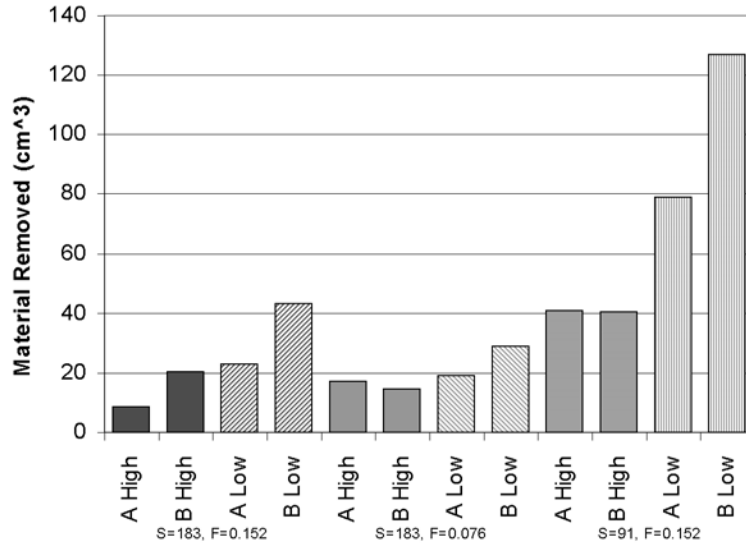


Figure 9. Comparison of tool life for different CBN grades and conditions

## 5. CONCLUSIONS

Hard turning is an emerging technology that can potentially replace many grinding operations due to improved productivity, increased flexibility, decreased capital expenses, and reduced environmental waste. A limited understanding about the wear and failure of the brittle cutting tools used in hard turning remains one of the biggest obstacles to further implementation of this technology. To understand both the wear behavior and life of different CBN grades, full tool life studies were performed for a test matrix consisting of seventeen cutting conditions with four different tool materials. Results of this study indicate that cutting speed has a more dramatic effect on tool life than feed or depth of cut. In general, increased feed rates were found to decrease tool life in minutes, but increase the amount of material removed with the tool. The crater and flank wear behavior before tool failure was also monitored throughout the life of each tool. Significant changes in cutting geometry were recorded, resulting from crater wear on the chamfered cutting edge. Flank wear behavior showed a repeating trend that is being investigated further to develop the ability to confidently predict tool life over a wide range of conditions.

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