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Environmentally conscious hard turning of cemented carbide materials on the basis of micro-cutting in SEM (2nd report): stress turning with three kinds of cutting tools †

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Abstract

Environmentally conscious hard turning and technology have placed increasing importance on the machining process. Cutting fluids have a significant impact on the environment, thus numerous research works are being performed to minimize their use. However, tool wear is very severe in hard turning cemented carbides without the use of cutting fluids. In this research, the effects of dry and wet cutting methods (vegetable oil mist and mineral oil) and tool material on cutting resistance and wear characteristics of cutting tools were experimentally investigated to study the possibility of creating an environmentally conscious hard turning of cemented carbides. Mist and wet cutting of the cemented carbides using poly-crystalline diamond (PCD) cutting tools were adopted to investigate how tool wear on the basis of micro-cutting in the Scanning Electron Microscope (SEM) can be reduced. Additionally, the poly-crystalline cubic boron nitride (PcBN) and the usual cBN cutting tools were compared with the PCD cutting tools.

Keywords: Environmentally conscious hard turning; Cemented carbide materials; Tool wear; Cutting resistance; Mist cutting; PCD; PcBN; cBN

1. Introduction

The hard turning process can be defined as a single-point machining process (i.e., one carried out on a lathe) performed on “hard” materials, where “hard” is defined as having a Rockwell C hardness greater than 45. The process is intended to replace or limit traditional grinding operations that are expensive, environmentally unfriendly, and inflexible.

Hard turning, when applied for purely stock removal purposes, competes favorably with rough grinding. The greatest advantage in using finish hard turning is the reduced machining time and complexity required to manufacture metal parts. The major benefits of hard turning compared with cylindrical grinding come from process flexibility, lower energy costs, and environmentally friendly aspects. Other benefits are detailed in the literature [1, 2].

Environmentally conscious hard turning and technology have placed increasing importance in the machining process. Since the cutting fluid has a significant impact on the environment, considerable research is being carried out to minimize its use. However, tool wear is very severe when cemented carbides materials are hard turned without the use of a cutting fluid.

The cemented carbides with wear and impact resistance have high hardness and strength, and their physical properties are very stable. Owing to their characteristics, they are used as cutting tools, dies, rolls, and so on. On the other hand, they are a difficult-to-cut material, and it is well known that tool

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wear is very severe in cutting using the polycrystalline diamond (PCD) tool [3-7].

In a previous study, turning [8] and micro-cutting in the Scanning Electron Microscope (SEM) [9-12] were carried out to better define the tool wear mechanism.

In the turning test, the relation between the tool wear and the cutting forces was clarified. In the micro-cutting test, the behavior of tungsten carbide (WC) particles in the deformation zone around the tool edge was observed in detail. However, these experiments were carried out under the limited conditions of the PCD tool and the dry cutting method.

The hard turning tests of four kinds of cemented carbides were carried out with the PCD tool using three cutting methods to investigate the possibility of an environmentally conscious hard turning and the influence of WC and binders in the previous study [13]. From the result, the possibility of an environmentally conscious hard turning of cemented carbides was observed. In the result of the orthogonal micro-cutting in SEM, it is observed that the tool wear on the flank was effectively reduced due to the lubricant percolating through the cracks in the mist and wet cutting methods.

At first, dry turning was carried out using polycrystalline cubic boron nitride (PcBN) [14] and the usual cBN tools to compare the results with those obtained using the PCD tool. The PcBN is attracting attention as the tool material to replace PCD. The tool wear width and cutting force were measured and the worn tool and chip were observed. The difference of the tool wear mechanism among the three tool materials was investigated.

Next, the mist and wet cutting of the cemented carbides were carried out. The mist cutting has been the most effective cutting method because the amount of cutting fluid is small and the environmental impact is comparatively little [15]. The cutting fluid is generally used for lubrication, cooling, and chip disposal. The validity of these two methods for cutting the cemented carbide was investigated from the tool wear width and cutting temperature.

2. Experimental method

2.1 Work material

The work material is V30 grade of cemented carbide. The chemical compositions and the mechanical properties are shown in Tables 1 and 2, respectively. This work material contains 90 wt% WC and 10 wt% Co, and the WC particle diameter is about 5 - 10 μm. Its hardness and compressive strength are 88.5 HRA and 4.61 GPa, respectively. As this cemented carbide has strong mechanical properties, it is widely used as a cutting tool, a mining tool, and a bit tip, among other uses.

Table 1. Chemical composition of cemented carbide V30 (wt%).

Cemented carbide	WC	Co
V30	90	10

Table 2. Mechanical properties of cemented carbide V30.

Cemented carbide	Specific gravity [Mg/m^3]	Hardness [HRA]	Compressive strength [GPa]	Young's modulus [GPa]
V30	14.4	88.5	4.61	578

Table 3. Mechanical properties of tool materials.

Tool	Diamond / cBN contents [Vol%]	Diamond / cBN Grain size [μ[Ed 101]m]	Hardness [GPa]	Transverse rupture strength [GPa]
PCD	91.0	12.5	100	1.7
cBN	80-90	1-3	38-41	0.95-1.1
PcBN	>99.9	<0.5	50-55	1.35

The work area is hollow. The inside and outside diameters are 90 mm and 110 mm, respectively. The length is 200 mm. In cutting the cemented carbides, the work is strongly supported on the dead center point, although it is mentioned later that the thrust force is large.

2.2 Tool material

The three kinds of tool materials were used. Their mechanical properties are shown in Table 3. The PCD and cBN tool materials are usually used while the PcBN is a new tool material. The PCD and cBN contain about 10 vol% binder, but the PcBN contains very little binder hexagonal boron nitride (hBN). This PcBN exhibits more excellent mechanical properties than the usual cBN and is attractive as the tool material to replace the PCD.

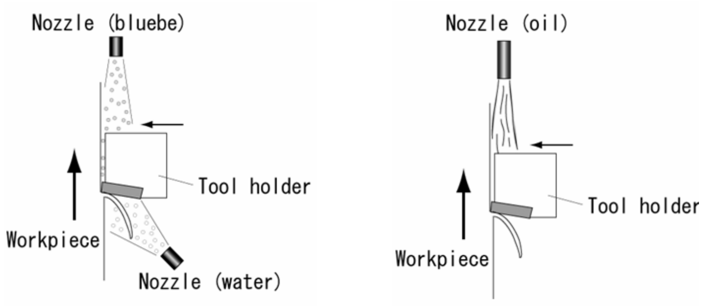


Fig. 1. Method of supplying cutting fluid.

Table 4. Mechanical properties of tool materials.

Cutting speed	15 (m/min)
Feed rate	0.1 (mm/rev)
Depth of cut	0.1 (mm)
Cutting method	Dry Wet (Mobil Sultran B3 : 150ml/min) Mist (Bluebe : 55ml/h, Water : 194ml/h)
Cutting tool dimension	(-5, -5, 5, 5, 30, 0, 0.8)

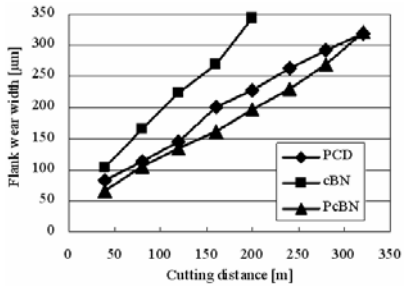


Fig. 2. Relation between flank wear width and cutting distance.

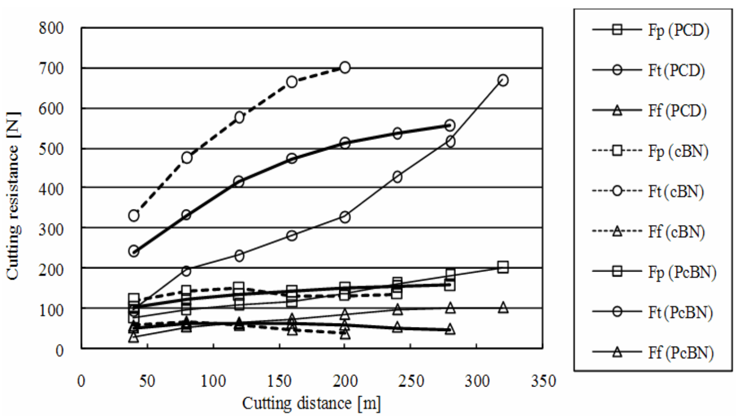


Fig. 3. Relation between cutting resistances and cutting distance.

2.3 Experimental apparatus and cutting conditions

In the turning test, a CNC lathe (HAKUSUITECH HTL-80) was used. The cutting conditions are shown in Table 4. The cutting speed was 15 m/min, the feed rate 0.1 mm/rev, and the depth of cut 0.1 mm. The cutting tool geometry as (-5, -5, 5, 5, 30, 0, 0.8). Furthermore, the insert tool has a nose radius of 0.8mm and the fitted holder has an effective front rake angle of -5° and a side rake angle of -5°. The front clearance angle measures 5°, the side clearance angle 5°, and the front cutting edge angle 30°. The side cutting edge angle is nearly 0°.

The cutting methods are dry, wet (Mobil Sultran: 150 ml/min), and mist (Bluebe: 55 ml/h, Water: 194 ml/h). Fig. 1 shows the method of supplying the oil and water mist. The oil mist was supplied to the side of the flank for lubrication and the water mist was supplied to the face for cooling. The tool wear width, surface roughness, and cutting temperature were measured and the worn tool was observed with an optical microscope at the cutting distance of 280 m. In dry cutting, the tool wear width and the cutting forces were measured, and the tool wear was observed at every 40 m cutting distance.

In order to measure cutting forces, the tool holder was produced additionally and a tool dynamometer shown in a previous study [16] was made. The cutting forces were detected from the bending strain of four beams. The characteristic frequency of this tool dynamometer was 3.6kHZ.

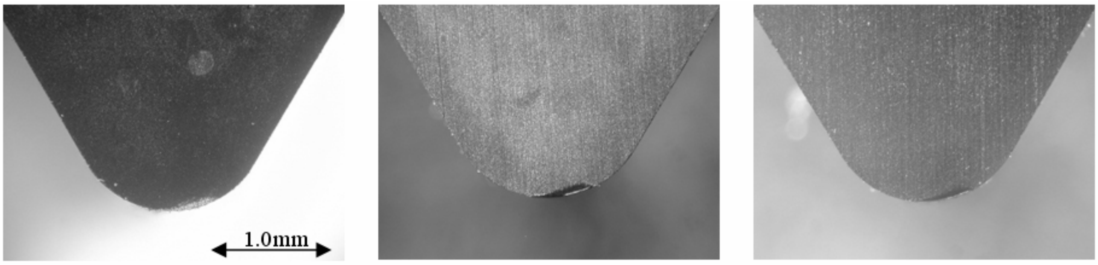
3. Result and discussion

3.1 Dry cutting with three tool materials

3.1.1 Flank wear width and cutting resistance

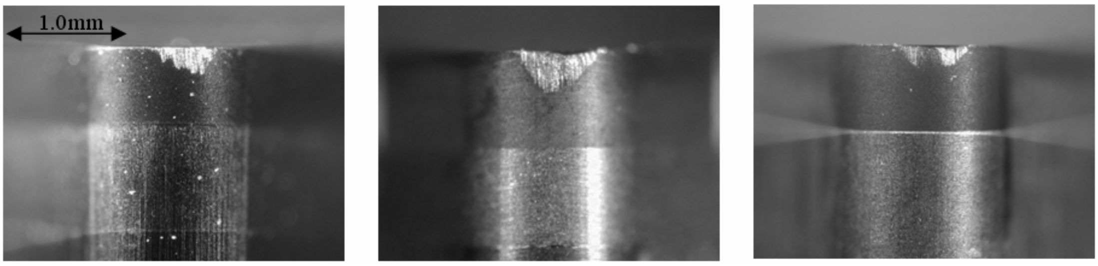
Fig. 2 shows the relation between the flank wear width and the cutting distance. The tool life criterion was defined when the flank wear width was more than 0.3 mm. The flank wear width of every tool material increased in proportion to the cutting distance. The tool life of cBN was shortest among the three tools because the cBN strength was weakest and the tool wear was mainly caused by a mechanical abrasion in the cutting of the cemented carbides.

Fig. 3 shows the relation between the cutting forces and the cutting distance. In this figure, the principle, thrust, and feed forces are indicated as Fp, Ft, and Ff, respectively. It is known that the thrust force is very large in the cutting of cemented carbides, and the



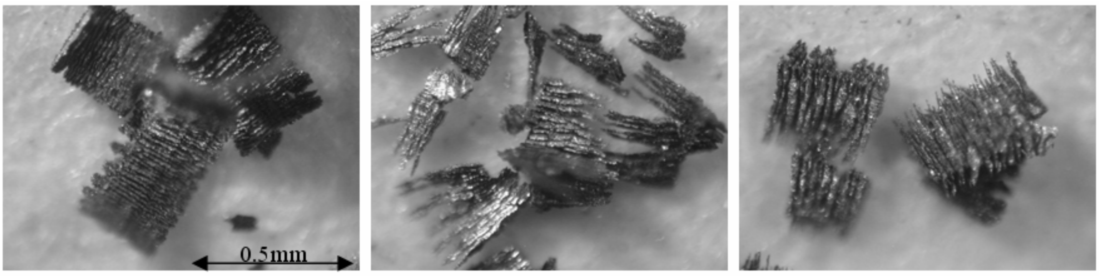
(a) PCD (b) cBN (c) PcBN

Fig. 4. Optical micro photographs of the face (cutting length: 40 m).



(a) PCD (b) cBN (c) PcBN

Fig. 5. Optical micro photographs of flank (cutting distance : 200 m).



(a) PCD (b) cBN (c) PcBN

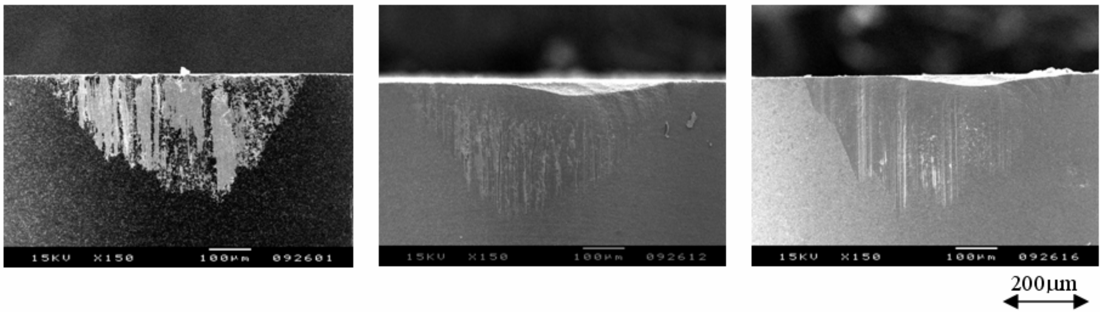
Fig. 6. Optical micro photographs of the chip (cutting distance: 160 m).

same tendency was shown in this experiment. The principal and feed forces of three tool materials showed a similar tendency and a nearly identical value. On the other hand, the thrust force of the cBN tool was largest while that of the PCD tool was smallest. It is believed that this is the reason why the greater the width of tool wear, the greater the contact width between the tool and the work piece.

3.1.2 Observation of worn tool and chip

Fig. 4 shows optical micro photographs of the face at the cutting distance of 40 m. When the dry cutting was carried out using the cBN and PcBN tools, tool failure was found at the tool edge. Although the cemented carbide seemed to adhere on the face of the PCD, the tool failure however could not be found.

Fig. 5 shows optical micro photographs of the flank at the 200 m cutting distance. The flank wear width of the cBN was very large and amounted to the tool life. The tool wear width of the PcBN tool was similar to that of the PCD tool, but the wear shape seemed to be different. The maximum wear width of the PcBN tool



(a) PCD (b) cBN (c) PcBN

Fig. 7. SEM photographs of the flank.

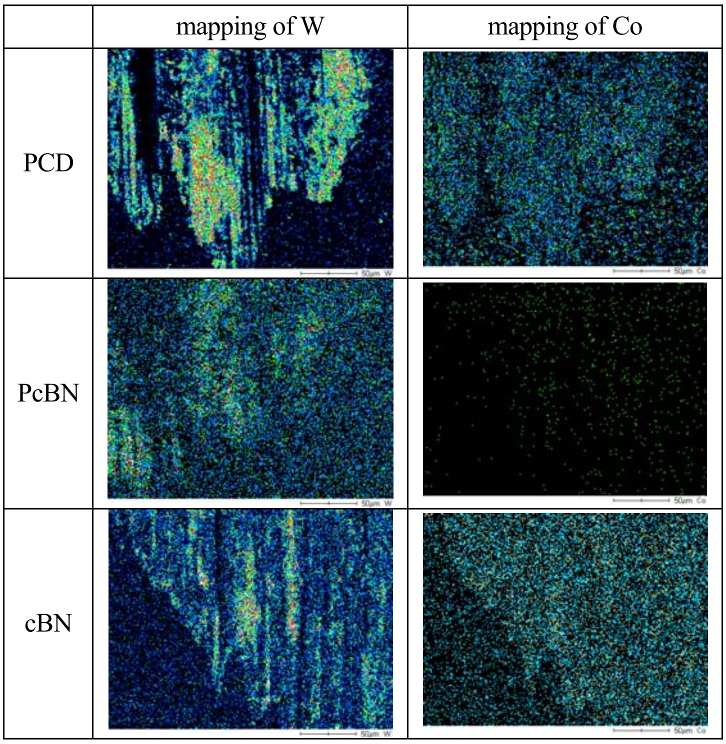


Fig. 8. EPMA data of the flank face.

was formed nearer the end of the cutting edge than that of the PCD tool. This is the reason why the face had failure from the early cutting because of the flaking.

Fig. 6 shows optical micro photographs of the chips at the cutting distance of 160 m. The chips were a shear type and were relatively continuous in cutting with the PCD tool. The chip of the PcBN was very short while that of the cBN became slightly longer than that of the PcBN. This is the reason why the cutting could not be carried out smoothly because of the face failure.

3.1.3 Adhesion on the tool flank

In the cutting of cemented carbides, tool wear causes not only the mechanical abrasion but also the adhesion. Therefore, the flank was observed with the SEM in order to investigate the existence of the adhesion. As shown in Fig. 7, the adhesion on the PCD tool was largest among the three tools while that on the PcBN could not be found. In order to investigate the composition of the cutting edge's adhesion in detail, the Energy Dispersive Spectroscopy (EDS) analysis was carried out using the Electron Probe Micro Analyzer (EPMA). It is observed in Fig. 8 that the adhesive material is a cemented carbide used as the work material. Moreover, the existence of Co, which was the binder of the PCD tool and the cemented carbide, seems to be connected to this adhesion.

3.2 Mist and wet cutting

3.2.1 Tool wear width and cutting temperature

To investigate the abovementioned reason, the cutting temperature on the face was measured. The thermocouple was pressed on the face at a point 0.2 mm away from the cutting edge as shown in Fig. 9.

The mist and wet cutting were continuously carried out till the cutting distance was 280 m. The flank wear width was then measured. As shown in Fig. 10, the tool wear width of the dry cutting was 230 μm and was largest among the three cutting methods. The flank wear width in the wet cutting was almost similar to that of the mist cutting, the maximum value of which was about 180 μm.

As shown in Fig. 11, the cutting temperature was comparatively low because of the low cutting speed. Although it is thought that the cutting temperature at

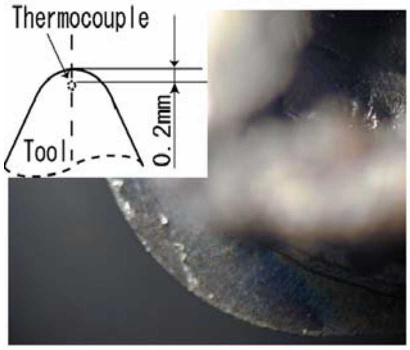


Fig. 9. Thermocouple on the face.

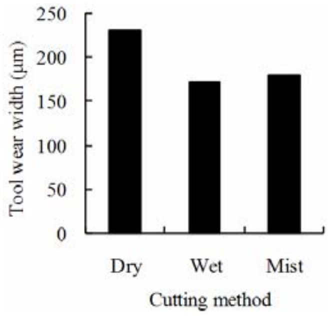


Fig. 10. tool wear width.

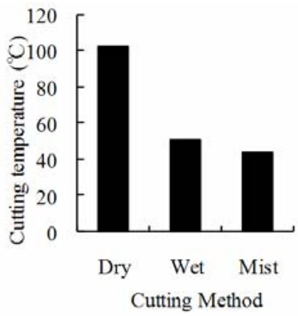


Fig. 11. Cutting temperature.

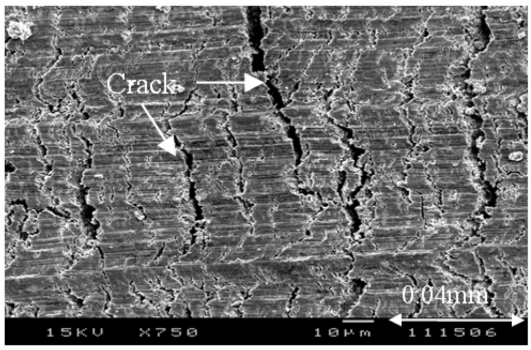
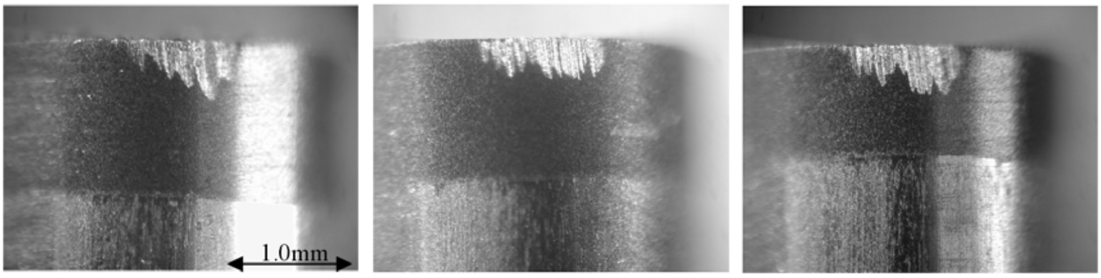


Fig. 12. Crack on chip in dry turning.



(a) Dry (b) Wet (c) Mist

Fig. 13. Optical micro photographs of flank (cutting distance : 280 m).

the cutting point becomes higher than this experimental value, it is considered that the reason the tool wear width becomes low is because of the lubrication rather than the cooling. Among the three cutting methods, wet cutting resulted in the lowest cutting temperature of 50.5° C; the cutting temperature of mist cutting was slightly higher.

Observing this cutting temperature tendency, the cutting temperature decreased due to the sufficient lubrication between the work piece and the flank in both mist and wet cutting. This cutting method has a cooling effect using vegetable oil mist and cutting fluid.

On the other hand, micro-cutting in the SEM using an orthogonal micro-cutting device for difficult-to-cut materials such as tungsten carbides in SEM [13] were carried out to clarify the phenomena of decreased tool wear and cutting temperature.

Fig. 12 shows the typical crack shape of the chip at micro-cutting in the SEM at a point 200μm after dry cutting at a 10 μm depth of cut using a PCD tool with the front rake angle α of 0°.

Observing this chip crack tendency, the tool wear decreased due to the sufficient lubrication between the crack in the mist and wet cutting. This cutting method has a cooling effect using the vegetable oil mist and cutting fluid. It is observed in Figs. 10 and 11 that the tool wear on the flank was effectively reduced due to the lubricant percolating through the cracks in mist and wet cutting.

3.2.2 Observation of the worn tool

The flank of the worn tool after the mist, wet, and dry cutting methods was observed in detail. Figure 13 shows each optical micro photograph. In the dry cutting, the tool wear width is at its maximum near the boundary of the depth of cut, but in the mist and wet setting, the tool wear is almost flat. It is thought that the effect of the lubrication works and prevents the tool wear from increasing.

4. Conclusions

The main results obtained are as follows.

(1) In mist or wet cutting, the tool wear decreased due to the sufficient lubrication between the work piece and the flank.

(2) The flank wear width in the usual cBN tool was largest among the three tools.

(3) At the cutting distance of 40 m, tool failure was found in the cBN and PcBN tools.

(4) Adhesion on the PCD tool was largest among the three tools, and the existence of Co, which was the binder of the PCD tool and the cemented carbide, seems to be concerned with this adhesion.

(5) The tool wear on the flank and the cutting temperature were effectively reduced due to the lubricant percolating in mist and wet cutting. In dry cutting, the tool wear width is at its maximum near the boundary of the depth of cut, but in the mist and wet cutting methods the tool wear is almost flat.

Acknowledgements

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