Tool wear of (Ti, Al) N-coated polycrystalline cubic boron nitride compact in cutting of hardened steel

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Abstract. Polycrystalline cubic boron nitride compact (cBN) is effective tool material for cutting hardened steel. In addition to coated high speed steel and coated cemented carbide that has long been used for cutting materials, more recently, coated cBN has also been used. In this study, to verify the effectiveness of the (Ti,Al)N-coated cBN, which is formed on the substrate of cBN by the physical vapor deposition method, the hardened steel was turned with the (Ti,Al)N-coated cBN tool at a cutting speed of 3.33, 5.00 m/s, a feed rate of 0.3 mm/rev and a depth of cut of 0.1 mm. Furthermore, the uncoated cBN, which was the substrate of the (Ti,Al)N-coated, was also used. The tool wear of the cBN tools was experimentally investigated. The following results were obtained: (1) The contact area between the rake face and the chip of the (Ti,Al)N-coated cBN tool was smaller than that of the uncoated cBN tool. (2) The tool wear of the (Ti,Al)N-coated cBN was smaller than that of uncoated cBN. (3) The wear progress of the (Ti,Al)N-coated cBN with the main element phase of the TiCN-Al, was slower than that of the (Ti,Al)N-coated cBN with the main element phase of the TiN-Al. (4) In the case of the high cutting speed of 5.00 m/s, the tool wear of the (Ti,Al)N-coated cBN was also smaller than that of uncoated cBN. The above results clarify that the (Ti,Al)N-coated cBN can be used as a tool material in high feed cutting of hardened steel.

1. Introduction

Many difficult-to-cut materials such as hardened steels, titanium and nickel based alloys, etc., are widely used today. For dimensional accuracy, these difficult-to-cut materials are required to be machined by the metal removal process. As these difficult-to-cut materials are required to be machined under high efficiency to improve productivity, it is necessary that the tool materials have good wear-resistance. Polycrystalline cubic boron nitride compact (cBN) seems to be an effective tool material because it has better features as a tool material such as good heat resistance, high hardness, etc. Therefore, regarding the cutting of hardened steel, which is one of these difficult-to-cut materials, there are many studies on the tool wear [1-3], the cutting force [4]-[5] or the surface roughness [6] of cBN tools. The cutting performance of cBN tools depends on the cBN contents rate [7], and the binding phase [8]. Therefore, an effective binding phase, etc. for cBN tools should be selected for the cutting of hardened steel.

On the other hand, coating has long been applied to high speed steel and carbide tools, and more recently, on cBN substrates [9]. Reginaldo T. Coelho et al. reported that in turning a hardened ASTM A29 4340 nickel chromium molybdenum steel (AISI 4340) using three types of coated cBN tool, namely the (Ti,Al)N-nano-coated, (Ti,Al)N-coated and (Al,Cr)N-coated, and uncoated cBN tool, the
lowest tool wear happened with the (Ti,Al)N-nano-coated cBN tool followed by the (Ti,Al)N-coated, (Al,Cr)N-coated and uncoated cBN tool [9].

A hardened ASTM 52100 bearing steel (DIN 100Cr6, 62 HRC) was turned by two types of coated cBN tool, namely the (Ti,Al)N- and TiN-coated cBN tool, and uncoated cBN tool. As a result, the experimental results showed that in the case of the lower feed rate of 0.08 mm/rev, there is little difference in tool life between the coated and uncoated cBN. However, in the case of the higher feed rate of 0.15 mm/rev, the tool life of coated cBN is longer than that of the uncoated tool, in particular the tool life of (Ti,Al)N-coated cBN is three times longer than that of the uncoated cBN tool [10].

It was reported that the coated cBN tool demonstrated longer tool life (~20%) than the uncoated tool life at a cutting speed of V<300 m/min, and the difference in tool life between the coated and uncoated CBN tool is negligible when V>300 m/min in high speed turning of Inconel 718 with the uncoated and coated cBN tool [11]. Moreover, it was reported that at a cutting speed of 250 m/min, the coated cBN tools had approximately 20% longer tool life than uncoated cBN, and the gap was rapidly closing with the increase in speed and became negligible at a speed of 350 m/min in turning of Inconel 718 with the uncoated and coated cBN tools [12].

In this study, in order to verify the effectiveness of the (Ti,Al)N-coated cBN, which is formed on the substrate of cBN by the physical vapor deposition (PVD) method, the hardened steel was turned with the (Ti,Al)N-coated cBN tool at a cutting speed of 3.33, 5.00 m/s, a feed rate of 0.3 mm/rev and a depth of cut of 0.1 mm. Furthermore, an uncoated cBN, which was the substrate of the (Ti,Al)N-coated, was also used. The tool wear of the cBN tools was experimentally investigated.

2. Experimental procedure

The work material used is hardened ASTM D2 cold-worked die steel (60 HRC). The chemical composition of the hardened steel is shown in Table 1. The tool materials used were a (Ti,Al)N-coated cBN by the PVD method. The substrate of the (Ti,Al)N-coated cBN is shown in Table 2. Furthermore, an uncoated cBN, which was the substrate of the (Ti,Al)N-coated cBN, was also used. The main element phase of the cBN A, cBN B and cBN C is TiCN-Al, TiN-Al and TiN-Al, respectively. The three types of cBN have different cBN content rates and different main binding phases. The tool wear of the cBN tools was experimentally investigated.

This investigation will contribute to the improvement of productivity in the case of high feed cutting hardened steels.
The turning tests were conducted on a precision lathe (Type ST5, SHOUN MACHINE TOOL Co., Ltd.) by adding a variable-speed drive. The driving power of this lathe is 7.5/11 kW with a maximum rotational speed of 2500 min\(^{-1}\). Hardened steel was turned under the cutting conditions shown in Table 3, and the tool wear was investigated.

**Table 1.** Chemical composition of the hardened steel (AISI D2, 60HRC).

|   | C  | Cr   | Mo  | Mn  | Si  | V   |
|---|----|------|-----|-----|-----|-----|
|   | 1.47 | 11.5 | 0.82 | 0.37 | 0.32 | 0.20 |

**Table 2.** Properties of polycrystalline cubic boron nitride compact.

| Tool material | Binding phase * | Contents rate ** | cBN particle size [μm] | Hardness [HV] | T. R. S. [GPa] |
|---------------|----------------|------------------|------------------------|--------------|----------------|
| cBN A         | TiCN-Al        | 45/55            | 5.0                    | 2700-2900    | 0.80-0.90      |
| cBN B         | TiN-Al         | 65/35            | 3.0                    | 3200-3400    | 1.00-1.10      |
| cBN C         | TiN-Al         | 75/25            | 5.0                    | 3500-3700    | 1.15-1.30      |

*: Main element, **: (cBN grain/ binding phase), T. R. S.: Transverse-rupture strength

**Table 3.** Cutting conditions.

- Cutting speed \(V=3.33, 5.00\) m/s
- Feed rate \(f=0.3\) mm/rev
- Depth of cut \(ap=0.1\) mm
- Cutting method Dry

![Configuration of a chamfered and honed cutting edge.](image)

**Figure 1.**

3. Results and discussion

Figure 2 shows the tool wear of uncoated and (Ti,Al)N-coated cBN tools. Figures (i), (ii) and (iii) show the case of cBN A, cBN B and cBN C, respectively. Figures (a) and (b) show the case of the uncoated cBN and (Ti,Al)N-coated cBN, respectively. In this figure, “L” is the cutting distance. In all the cBN tools, the grooved abrasive traces can be found on the worn surface of the flank, and the flank wear is parallel to the cutting edge. Therefore, the maximum value of the flank wear width (VBmax) was measured with a microscope.

Figure 3 shows the relation between the cutting distance and the flank wear width at a cutting speed of 3.33 m/s with uncoated cBN A and (Ti,Al)N-coated cBN A tools. The wear progress of the (Ti,Al)N-coated cBN A is slower than that of uncoated cBN A.

As described above, the wear progress of the (Ti,Al)N-coated cBN A is slower than that of uncoated cBN A. The reason for this is as follows. At first, Figure 4 shows the detail of the worn surface on the rake face. Namely, Fig. 4(a) shows the uncoated cBN A and the detail of A is shown in Fig. 2 (i)(a), and Fig. 4(b) shows the (Ti,Al)N-coated cBN A and the detail of B is shown in Fig. 2 (i)(b). In Fig.
4(b), the “A” shows the contact width between the rake face and the chip and “B” shows the contact length between the rake face and the chip.

(a) Uncoated, L=225 m  (b) (Ti,Al)N-coated, L=445 m

(i) cBN A

(a) Uncoated, L=225 m  (b) (Ti,Al)N-coated, L=298 m

(ii) cBN B

(iii) cBN C

(L: Cutting distance)

Figure 2. Tool wear in cutting hardened steel at a cutting speed of 3.33 m/s, feed rate of 0.3 mm/rev and depth of cut of 0.1 mm.

Figure 3. Relation between the cutting distance and flank wear width at a cutting speed of 3.33 m/s with (Ti,Al)N-coated cBN A and uncoated cBN A.

Figure 4 shows the wear photographs on the rake face of cBN A. Table 4 shows the “S” and the dimensions of “A” and “B” shown in Fig. 4. In Table 4, the “S” is the area of the worn surface on the rake face shown in Fig. 4. Compared with uncoated and (Ti,Al)N-coated cBN tool, both the “S” and
the “A”, “B” of the (Ti,Al)N-coated cBN tool are smaller than that of the uncoated cBN tool in the case of all cBN tools. The contact area between the rake face and the chip of the (Ti,Al)N-coated cBN tool is smaller than that of the uncoated cBN tool. That is, the (Ti,Al)N-coated cBN A has a smaller contact area between the rake face and the chip as compared with the uncoated cBN A. Therefore, it is considered that in the case of cutting hardened steel by the (Ti,Al)N-coated cBN A tool, the cutting temperature decreases with the decrease of the friction force between the rake face and the chip. R. M’Saoubi et al. reported also that the tool temperature of (Ti,Al)N-coated cBN is lower, about 10 ºC, than that of uncoated cBN in cutting hardened steel 16MnCr5 (58-62 HRC) with the four types of coated cBN tools [14]. This is considered to be the reason why there is less tool wear of the (Ti,Al)N-coated cBN A tool.

Next, Figure 5 shows the EDS mapping analysis on the worn surface of the two types of uncoated and (Ti,Al)N-coated cBN A tools. In Fig. 5, the EDS analysis for the iron (Fe) and oxygen (O) mapping on the cutting part is shown. As compared with the iron element on the worn surface of the uncoated cBN A tool and that of the (Ti,Al)N-coated cBN A tool, the Fe element on the uncoated cBN A tool shown in Fig. 5(a) is less than that on the (Ti,Al)N-coated cBN A tool shown in Fig. 5(b) due to the cutting distance of the (Ti,Al)N-coated cBN A tool that is almost twice that of the uncoated cBN A tool. However, there is little difference between the oxygen element of the uncoated cBN A and that of the (Ti,Al)N-coated cBN A tool, which was turned at a long cutting distance. Therefore, the cutting temperature of the (Ti,Al)N-coated cBN A tool is about the same as that of the uncoated cBN A tool despite the increase in the cutting distance of the (Ti,Al)N-coated cBN A tool.

![Wear photographs on the rake face of cBN A.](image)

**Figure 4.** Wear photographs on the rake face of cBN A.

| Tool material | Coating film | S $\times 10^{-3}$ mm$^2$ | A [mm] | B [mm] |
|---------------|--------------|--------------------------|--------|--------|
| cBN A         | Uncoated     | 68.9                     | 0.575  | 0.173  |
|               | (Ti,Al)N     | 53.7                     | 0.565  | 0.140  |
| cBN B         | Uncoated     | 80.0                     | 0.574  | 0.220  |
|               | (Ti,Al)N     | 63.8                     | 0.498  | 0.161  |
| cBN C         | Uncoated     | 91.3                     | 0.642  | 0.211  |
|               | (Ti,Al)N     | 64.2                     | 0.588  | 0.166  |

S: Area of worn surface on the rake face shown in Fig. 4
A: Contact width between the rake face and the chip shown in Fig. 4(b)
B: Contact length between the rake face and the chip shown in Fig. 4(b)
Figure 5. EDS mapping analysis of iron and oxygen on the worn surface (a) uncoated, (b) (Ti,Al)N-coated cBN A tool.

Figure 6 shows the relation between the cutting distance and the flank wear width at a cutting speed of 3.33 m/s with the three types of cBN tools. The wear progress of the (Ti,Al)N-coated cBN A is slowest. Comparing the cBN particle size of the three types of cBN shown in Table 2, the three types of cBN have approximately the same cBN particle size of 3.0–5.0 μm. Next, comparing the cBN contents rate of the three types of the cBN, the cBN contents rate of the cBN A, which has 45% cBN content, is the least. Furthermore, both the hardness and the transverse rupture strength of cBN A are the least, too. However, the tool wear of the (Ti,Al)N-coated cBN A is the smallest among the three types of cBN tool. This is due to the following reasons. That is, in the case of high feed rate cutting, the cutting temperature rises. K. Shintani et al. carried out a heated test on cBN tools with various binding phases under the experimental conditions of a temperature of 1273 K and a holding time of 600 s in an Ar atmosphere, and it was inferred that because a part of TiN, which is the main binding phase of cBN, changes to the brittle material TiO$_2$, the binding strength of the cBN decreases [16]. Therefore, at high feed rate cutting, because a part of TiN, which is the main binding phase of both the cBN B and the cBN C tool, changes to the brittle material TiO$_2$, the binding strength of the cBN decreases, and the tool wear of both the cBN B and the cBN C becomes larger than that of the cBN A, which has the main binding phase of TiCN-Al.

As described above, the (Ti,Al)N-coated cBN A tool is the most effective tool material in the cutting of hardened steel.

Figure 7 shows the relation between the cutting distance and the flank wear width at a cutting speed of 5.00 m/s with two types of cBN A tools. In the case of the higher cutting speed, the wear progress of the (Ti,Al)N-coated cBN A is also slower than that of the uncoated cBN A.
4. Conclusion
In this study, in order to verify the effectiveness of the (Ti,Al)N-coated cBN, which is formed on the substrate of cBN by the PVD method, the hardened steel was turned with the (Ti,Al)N-coated cBN tool at a cutting speed of 3.33, 5.00 m/s, a feed rate of 0.3 mm/rev and a depth of cut of 0.1 mm. Furthermore, the uncoated cBN, which was the substrate of the (Ti,Al)N-coated, was also used. The tool wear of the cBN tools was experimentally investigated. The following results were obtained:

- The contact area between the rake face and the chip of the (Ti,Al)N-coated cBN tool was smaller than that of the uncoated cBN tool.
- The tool wear of the (Ti,Al)N-coated cBN was smaller than that of the uncoated cBN.
- The wear progress of the (Ti,Al)N-coated cBN with the main element phase of the TiCN-Al was slower than that of the (Ti,Al)N-coated cBN with the main element phase of the TiN-Al.
- In the case of the high cutting speed of 5.00 m/s, the tool wear of the (Ti,Al)N-coated cBN was also smaller than that of the uncoated cBN.

These results clarify that the (Ti,Al)N-coated cBN can be used as a tool material in high feed cutting hardened steel.

5. References
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