Studies on Turning Difficult-to-Machine Materials with Super Hard Tools — Cutting characteristics of titanium alloy and sintered carbide —

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学位論文要旨

Studies on Turning of Difficult-To-Machine Materials with Superhard Tools – Cutting Characteristics of Titanium Alloy and Cemented Carbide

超硬質工具による難削材の旋削加工に関する研究
—チタン合金および超硬合金の切削特性—

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Studies on Turning Difficult-to-Machine Materials with Super Hard Tools - Cutting Characteristics of Titanium Alloy and Sintered Carbide

Abstract

This study concentrating on the cutting performance of super hard cutting tools such as CBN (Cubic Boron Nitride) and diamond in turning difficult-to-machine materials. Two types of typical difficult-to-machine materials are chosen: titanium alloy and cemented carbide. Titanium alloy is used in aerospace, power generation and several other industries owing to its high weight-to-strength ratio and excellent corrosion resistance whereas cemented carbides are commonly used for molds, dies and cutting tools due to its high hardness. The poor machinability of titanium alloy Ti-6Al-4V is characterized by its low thermal conductivity and strong alloying tendency or chemical reactivity with tool materials. On the other hand, serious tool wear takes place in cutting cemented carbide due to its high hardness. It is certain that in cutting titanium alloys, tools with singular crystal structure and very high thermal conductivity is preferred. Meanwhile in cutting cemented carbide, binderless tool with very small sized crystal/grain structure with high hardness is recommended. This tool has been seen to be suitable candidate for cutting cemented carbide.

1.0 Introduction

Difficult to machine material is generally classified as material that reduces tool life at high rate, induced unmaintainable accuracy on the machined dimension and surfaces and required more machining time. There are several materials which are categorized as difficult to machine materials, but the most common known are titanium alloys and cemented carbide.

Cemented carbides, which are commonly used for molds, dies and cutting tools, are currently machined or shaped by grinding and/or EDM in order to form the exact desired dimension. In grinding of cemented carbides, an expensive diamond grinding wheel is needed and the MRR (Material Removal Rate) is very low as well as EDM process. In order to reduce the post casting/sintering processes, cemented carbides are being produced in near net shape form. This has encouraged researchers to find alternative post-processing methods in producing precision tools, molds and dies without sacrificing quality of the surface finish.

Meanwhile, titanium alloy (Ti-6Al-4V) has been used in in aerospace, automotive, chemical plant, power generation, medical applications and several other industries owing to its properties such as high strength, low weight (weight-to-strength ratio) and excellent corrosion resistance. In order to utilize these outstanding materials as machine components, it is necessary to machine with desired sharp, accuracy, integrity and productivity. A serious tool wear, however, occurs when titanium alloy is machined because the low thermal conductivity of the material causes the high cutting temperature [1, 2]. A strong alloying tendency or chemical reactivity with materials also promotes galling, adhesion and diffusion/dissolution of tool materials [3, 4].

These materials have opposite condition in cutting of each material as titanium induce high cutting temperature and chemically unstable condition and cemented carbide is simply a very hard material that commonly chips the cutting tool during cutting.

This thesis touches about the cutting of titanium alloy and cemented carbides in high speed and severe condition turning with selected diamond tools.

2.0 Methodology

The internal turning experiments with cutting fluid in cutting Ti-6Al-4V and without cutting fluid in cutting cemented carbide are carried out using the vertical machining center. The cutting condition for both titanium alloy and cemented carbide cutting are shown in Table 1 and Table 2 respectively.

Table 1 Experimental conditions

Cutting tool (Binderless diamond)		Single crystal: SC Nano-polycrystalline: BL-NPD
Rake angle	α	0°
Nose radium	r_ε	0.8 mm
Workpiece		Ti-6Al-4V
Cutting speed	v	300 m/min
Depth of cut	a	0.2 mm
Feed rate	f	0.1 mm/rev
Cutting style		Wet (q_c=6 ℓ/min)
Coolant		Emulsion (1:30 in water)
Air supply		0.6 MPa

Table 2 Cutting conditions.

Workpiece			Cemented carbide (WC-m, WC-d, WC-t)
Insert (Nose radius: r_ε = 0.8 mm)			CBN, PCD-a, PCD-b, BL-NPD, SC, CVD-SC
Cutting speed	v	m/s	40
Depth of cut	d	mm	0.05
Feed	f	mm/rev	0.1
Cutting style			Dry

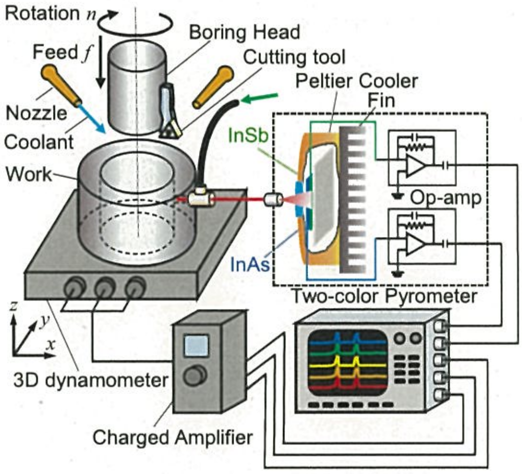


Fig. 1 Experimental setup of internal turning

The cutting performance of each tool is evaluated by cutting force, cutting temperature, surface roughness and tool wear. Cutting force, cutting temperature, tool wear and surface roughness are measured by the 3-axis piezoelectric dynamometer, two-color pyrometer, stylus profilometer and SEM, respectively. Fig. 1, shows the experimental set up for titanium alloy cutting experiment.

Cutting temperature is measured using two color pyrometer of Indium Arsenide (InAs) and Indium

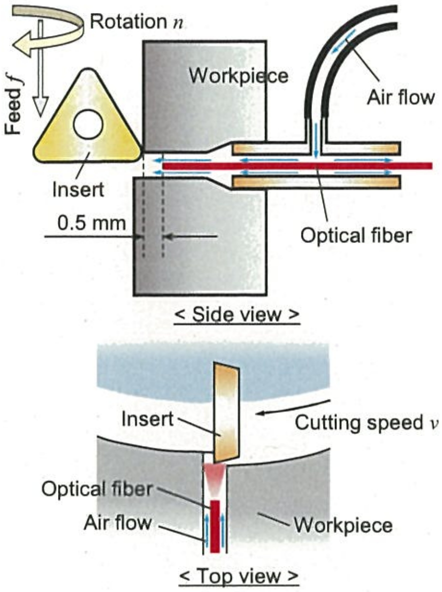


Fig. 2 Cutting temperature measurement in wet cutting

Antimonite (InSb) photodetectors. These detector converted infrared radiation collected from the tool flank face by chalcogenide optical fiber to the electrical signals. These electrical signals values in volts are calculated to tool flank temperature. This temperature is assume to be cutting temperature. In wet cutting, pressurized air supply is needed to reduce ingress of coolant on the fiber shown in Fig. 2. This setting of supplying pressurized air is not needed in dry cutting on cemented carbides.

3.1 High Speed Wet Cutting of Titanium Alloy with Diamond Tools

The measured tool wear and tool flank temperature is shown in Fig. 3 and Fig. 4 respectively. Here, it is evident that SC tool performed admirably in comparison in comparison to BL-NPD. SC tool wears slower and experienced lower cutting temperature than BL-NPD in cutting titanium alloy.

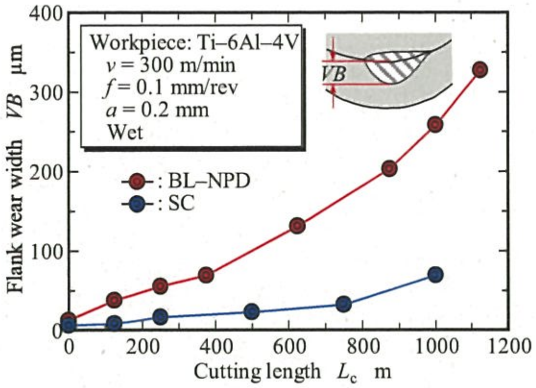


Fig. 3 Change of flank wear width with cutting length

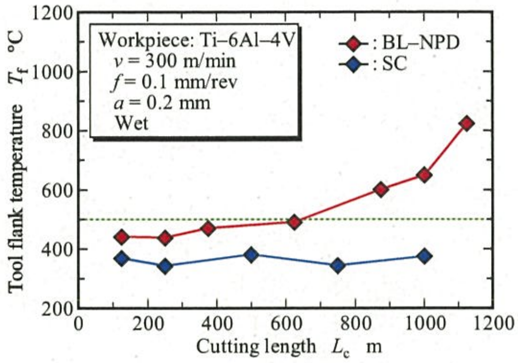


Fig. 4 Change of tool flank temperature with cutting length

Fig. 4 presents the microscopic images of the worn rake and flank faces of the BL-NPD tool. The tool is etched by 1% HF-HNO3 in order to remove the bonded Ti-6Al-4V whereas adhered materials are partially remained. As shown in the figure, very smooth surface without scratch marks are observed and this result suggests that the diffusion wear is dominant rather than attritious wear.

Based on research done by Nabhani et al. [5], the smooth feature on flank face and crater is due to diffusion-dissolution wear of the tools. The diffusion-dissolution wear occurs with some combination of tool (C) and work material (Ti) and it promotes at high cutting temperature than 500ºC.

The SEM/EDX analysis is done on the cutting tools but the strongest evidence found in cutting chips cut by both tools. Fig. 6 shows the typical close-up images of the back surface of the chip strips and their element mapping with respect to carbon and titanium. The EDX mapping analysis reveals that there are many carbon (carbide) on the Ti-6Al-4V chips as shown in Fig. 18, and this tendency is prominent in cutting with BL-NPD tool. It is believe that TiC exists in these cutting chips due to chemical reaction in high temperature. Nabhani [5] and Klocke et al. [6] reported that TiC seems to inhibit the growth of tool wear in cutting titanium alloy with PCD tool due to the wear resistance properties on TiC, but it is not the case in this experiment whereby the suspected TiC formation is shown to be carried away by the passing chip based on the EDX analysis done. In the case of NPD, the tool wear acceleration by diffusion shows that the suspected TiC layer does not impede tool wear growth.

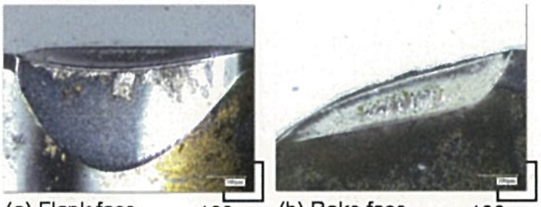
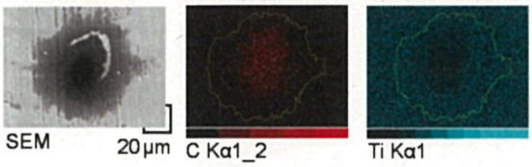

(a) Flank face 100 μm (b) Rake face 100 μm

Fig. 5 Microscopic image of NPD tool after etching by 1% $HF\text{-}HNO_3$

(a) SC tool (L_c=750 m)



(b) BL-NPD tool (L_c=875 m)

Fig. 6 SEM/EDX photographs and element mapping of back surface of cutting chips

Based on the results and discussion in the previous section, the diffusion-dissolution wear model in cutting Ti-6Al-4V with diamond tool are proposed. Fig. 7 demonstrates the diffusion-

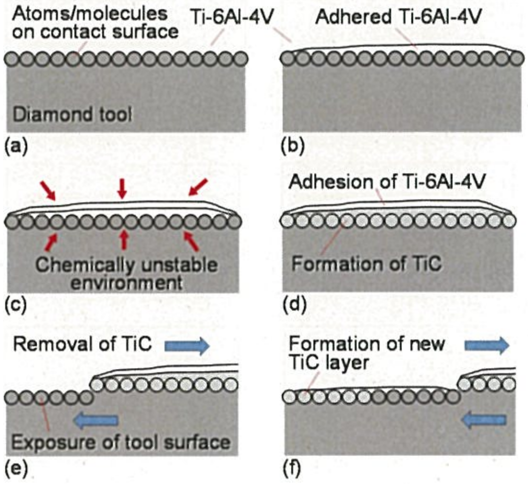


Fig. 7 Diffusion-dissolution wear model of diamond tool in cutting Ti-6Al-4V

dissolution wear model considered. During cutting, the workpiece material adheres to the tool surface (a), (b). As the cutting process continues, the chemically unstable environment makes the catalyst of the carbide forming (TiC) under the adhesion layer (c), (d). This carbide, that fuses carbon atoms on the tool surface and the titanium substrate in the adhesion, will be diffused and dissolved by the chip movement (e), (f). According to the above mechanism, a relatively large tool wear occurs in BL-NPD because of high cutting temperature above 500°C as shown in Fig. 4. Both tools are binderless and the work-tool combination is the same but the cutting temperature of BL-NPD is higher than that of SC tool. This has proven that thermal conductivity of tool's material has a great influence over tool wear [7].

3.2 Investigation of Hard Turning on Cemented Carbide with Diamond Tools

The experiment have been done on three different carbides with five types of cutting tools. Fig. 8 shows the change of flank wear width with cutting length L when the softest WC-m is cut. As shown in the figure, the polycrystalline CBN tool has the lowest tool wear than any PCD tools. This result is aligned to the previous report [8] that CBN wears slower than PCD tools in cutting WC with higher cobalt content. This is clear in the SEM pictures in Fig. 9. In the case of relatively soft carbide, the wear seems to depend on chemical reaction rather than mechanical attrition.

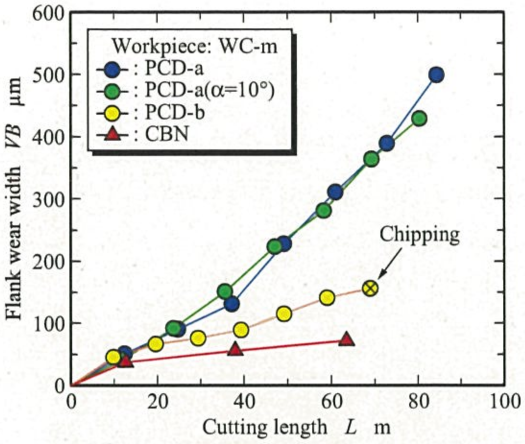


Fig. 8 Change of flank wear width with cutting length in turning of softest carbide WC-m.

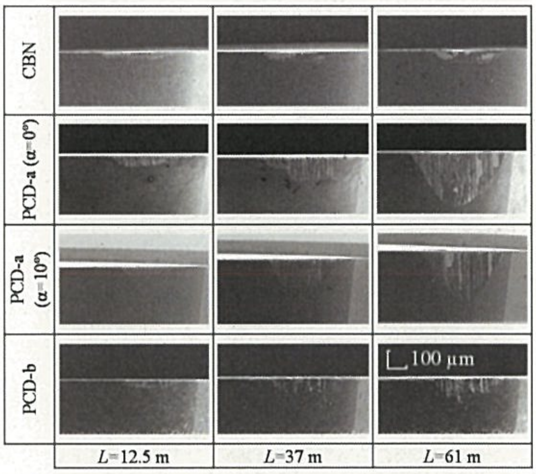


Fig. 9 SEM photographs of flank face with respect to Fig. 8.

Meanwhile the change of flank wear width with cutting length L in turning of harder WC-d and WC-t is shown in Fig. 10. In cutting of such hard carbide materials, both polycrystalline CBN and PCD cannot be used continuously due to their low hardness of the tool material, while BL-NPD and SC tools are applicable. Especially, only BL-NPD is well available for cutting of the hardest WC-t.

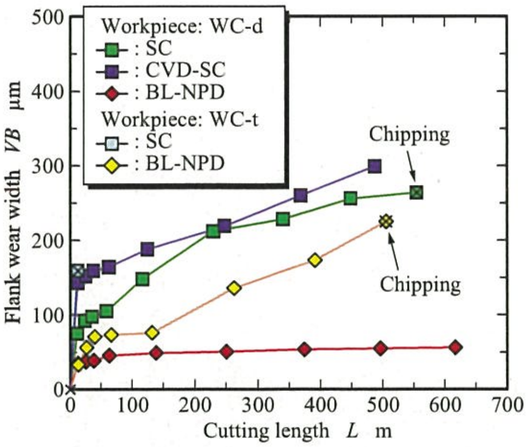


Fig. 10 Change of flank wear width with cutting length in turning of harder carbides WC-d and WC-t.

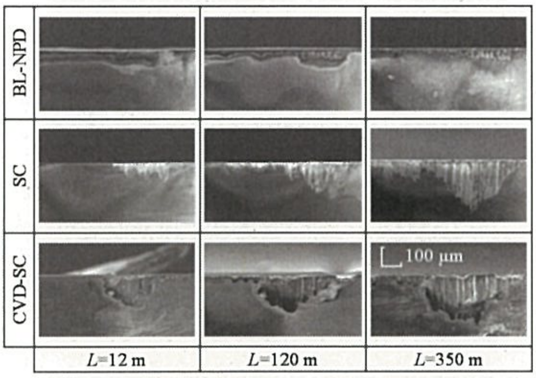


Fig. 11 SEM photographs of flank face in turning WC-d.

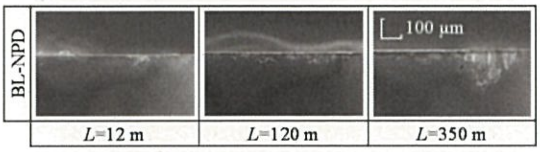


Fig. 12 SEM photographs of flank face in turning WC-t.

In turning of WC-d, the BL-NPD tool has the best cutting performance with less flank wear. In the case of SC tool, on the other hand, the flank wear with VB approaches approximately 270 μm at the cutting length of 560 m, and then chipping occurred at the same time. Fig. 11 represents the SEM photographs of tool flank and it is visible that the cutting edge geometry of BL-NPD is kept almost constant. Similar behavior is seen in CVD-SC because it has the similar physical properties as SC.

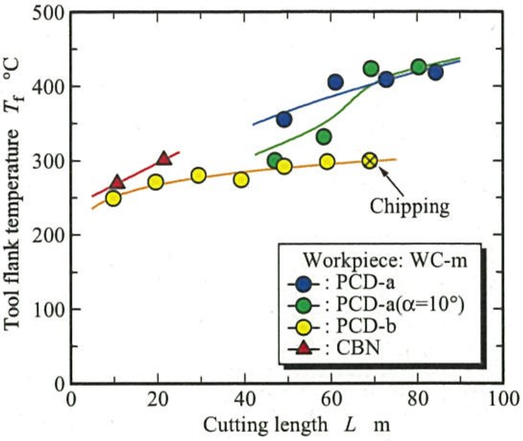


Fig. 13 Change of tool flank temperature with cutting length in turning of softest carbide WC-m.

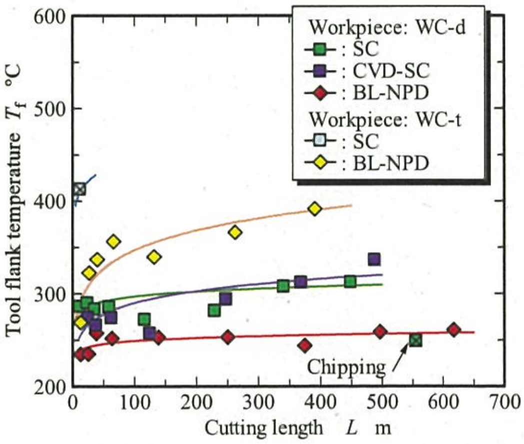


Fig. 14 Change of tool flank temperature with cutting length in turning of harder carbides WC-d and WC-t.

In the case of turning WC-t, the SC tool underwent the chipping at the initial stage of

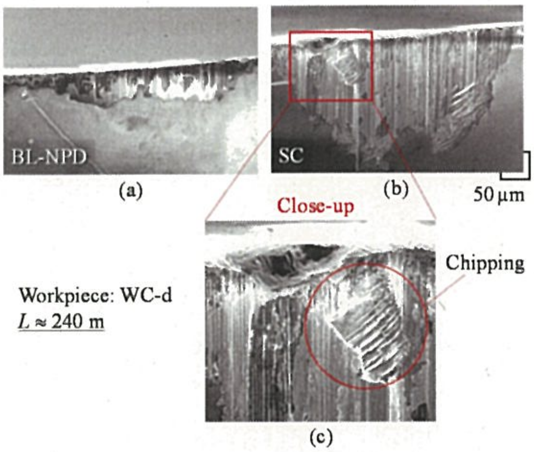
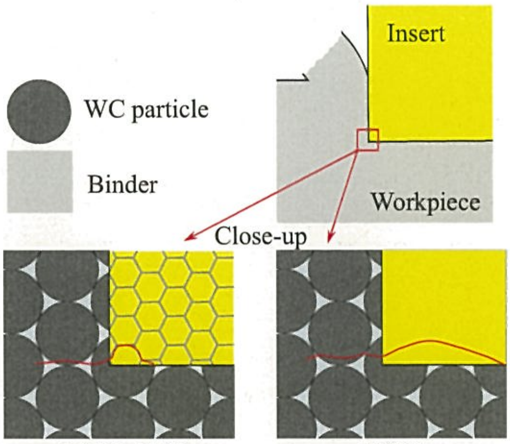


Fig. 15: Close-up SEM images of flank wear.



(a) BL-NPD (b) SC

Fig. 16 Crack propagation model in cutting tools.

cutting, whereas BL-NPD can continue to cut up to the cutting length of approximately 500 m. Due to this, only SEM pictures of BL-NPD is taken as shown in Fig.12.

Most of the tool experienced attrition as the main tool wear mechanism accompanied by some adhesion of the workpiece material. This is visible in Figs 9, 11 and 12.

Tool flank temperature is significantly low due to the high thermal conductivity of both workpiece and tool materials. This is shown in Figs 13 and 14. Thermal conductivity values indicate the ability of the tool and workpiece to channel the thermal energy away from the source as the higher the value, the quicker the thermal energy transferred to the surroundings. However, cutting temperature is more influenced by cutting force (tool wear) than thermal conductivity in the case of harder carbide WC-d and WC-t. This phenomenon is similar in WC-m cutting whereby although PCD-a have a higher thermal conductivity in comparison to CBN tool; it experienced much higher cutting temperature than CBN as shown in Fig. 13.

The tool performance is somehow related to the tool hardness value and the grain structure of the tool. BL-NPD with the grain structures size of several nm seem to perform better in cutting force and tool wear in comparison to single crystal structured SC tool. Comparable performance indication has also been seen in previous study [9] where similar tools are used in cutting binderless cemented carbide.

This wearing phenomenon is noticeable in Fig.15 and it is explained further in Fig. 16. It is apparent that the nano-grained tool wears more gracefully and the crack that formed chipping by exposed WC particles is being halted by another grain/particle or following the interface before it propagates to other areas in BL-NPD. This act reduces large chipping and the tool will usually sustain attrition wear. Meanwhile, the structure of

SC has been a factor of localized chipping. This is due to the nature of singular crystal. When the crack of the worn tool started, it will propagate and uncontrollable. This has been the reason of chipping that is shown visually on the tool edge.

4.0 Conclusions

The conclusion in this study is written in 2 parts; titanium alloy and cemented carbide cutting.

4.1 Titanium Alloy Cutting

Two types of binderless diamond tools: single crystal diamond (SC) and nano-polycrystalline diamond (BL-NPD): are applied to high speed turning of titanium alloy (Ti-6Al-4V) with water soluble coolant. The main results obtained are as follow.

a) The VB curve with respect to cutting length has a similar form to those of cutting force and tool flank temperature. The tool wear mechanisms seems to be related to adhesion of Ti-6Al-4V on the tool.

b) Diffusion-dissolution wear occurs in such a manner that the thin TiC layer is formed between a diamond tool and adhered Ti-6Al-4V material and it dissolves through the cutting chip. This wear model seems to be convictive by the fact that carbon is detected by EDX analysis.

c) The single crystal diamond (SC) shows better cutting performance in turning of Ti-6Al-4V at the cutting seed of 300 m/min. The nano-polycrystaline diamond (BL-NPD) is tough but it causes a high cutting temperature due to its low thermal conductivity and high tool wear rate

4.2 Cemented Carbide Cutting

Cutting performance of four types of diamond tools and CBN tool is examined in dry turning of three grades of cemented carbide (WC), where Co binder content is changed with 12%, 20% and 25%. The main results are summarized as follows.

a) In cutting of softest carbide WC-m (25% Co), the polycrystalline CBN tool has the lowest tool wear than any other PCD tools.

b) In turning of harder carbides WC-d (20% Co) and WC-t (12% Co), BL-NPD tool has the best cutting performance with less flank wear. As for WC-d, the extremely stable cutting can be done with BL-NPD where the principal cutting force is kept almost constant at 40 N.

c) In spite of turning hard materials, the tool temperatures measured are relatively low below 450°C due to the high thermal conductivities of tool materials. However, cutting temperature is directly related to the tool wear and cutting force rather than thermal conductivity in turning of WC-m and WC-t.

d) The stable finished surface is formed by clear feed mark having the cutting edge geometry in all carbides.

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学位論文審査報告書（甲）

１．学位論文題目（外国語の場合は和訳を付けること。）

Studies on Turning Difficult-to-Machine Materials with Super Hard Tools — Cutting characteristics of titanium alloy and sintered carbide — （超硬質工具による難削材の旋削加工に関する研究 ― チタン合金および超硬合金の切削特性 ―）

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３．審査結果の要旨（600～650字）

当該学位論文に関し，平成28年2月1日に第１回学位論文審査会を開催し，提出された学位論文および関連資料について詳細に検討した．更に，平成28年2月1日の口頭発表の後，第2回審査委員会を開催し慎重に協議した結果，以下の通り判定した．

本論文は，チタン合金 (Ti-6Al-4V) および超硬合金 (Tungsten carbide) の旋削加工において，超硬質工具 (CBNおよびダイヤモンド) の適用性を明らかにしたものである．チタン合金の切削では，切りくずの工具への凝着抑制の観点からバインダレスダイヤモンドが適していることを示した上で，その摩耗形態を工具表面に形成されたTiCが切りくずや工作物によって持ち去られる“拡散摩耗”が主体であることを明らかにしている．そして，この現象は切削温度が500°C以上で顕著になることから，高硬度のナノ多結晶ダイヤモンドよりも，熱伝導率が大きく切削温度が低い単結晶ダイヤモンドが適していることを示している．一方，超硬合金 (WC+Co) は摩滅摩耗が主体であるが，WC，Coの比率や焼結粒子径によって被削性が異なり，HV840程度の軟質材料ではCBN工具が適用できるが，HV970を超える硬質材料ではナノ多結晶ダイヤモンドのみ安定した加工が可能であることを明らかにしている．

以上のように，本論文は工具損耗形態が異なる２種類の難削材の旋削加工に関して有益な知見を得るなど学術的価値が高く，その内容は博士（工学）論文に値すると判定する．

４．審査結果　(1) 判　定（いずれかに○印）[✓ 合　格]・　不合格

(2) 授与学位　博　士（工　学）