Machining Characteristics of Cemented Carbides in Micro Cutting within SEM

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ABSTRACT

This research describes that the cutting characteristics and tool wear behavior in the micro cutting of three kinds of wear resistant cemented carbides (WC-Co; V40, V50 and V60) using PCD (Poly Crystalline Diamond) and PCBN (Polycrystalline Cubic Boron Nitride) cutting tools by use of the SEM (Scanning Electron Microscope) direct observation method. The purpose of this research is to present reasonable cutting conditions from the viewpoint of high efficient cutting refer to a precise finished surface and tool wear. Summary of the results is as follows: (1) The cutting forces tend to increase as the increase of the weight percentage of WC particles, and the thrust forces was larger than the principal forces in the cutting of WC-Co. These phenomena were different from the ordinary cutting such as cutting of steel or cast iron. (2) The cutting speed hardly influenced the thrust force, because of the frictional force between the cutting tool edge and small WC particles at low cutting speed region such as 2μm/s. It seemed that the thrust cutting force occurred by the contact between the flank face and work material near the cutting edge. (3) The wear mechanism for PCD tools is abrasion by hard WC particles of the work materials, which leads diamond grain to be detached from the bond. (4) From the SEM direct observation in cutting the WC-Co, it seems that WC particles are broken and come into contact with the tool edge directly. This causes tool wear, resulting in severe tool damage. (5) In the orthogonal micro cutting of WC-Co, the tool wear in the flank face was formed bigger than that in the rake face on orthogonal micro cutting. And the machining surface integrity on the side of the cutting tool with a negative rake angle was better than that with a positive one, as well as burr in the case of using the cutting tool with a negative rake angle was formed very little compared to the that with a positive one.

Key Words: WC-Co, Difficult-to-Cut materials, Micro cutting, Direct observation method, SEM, PCD, PCBN

1. Introduction

With the demand of lower costs, higher accuracy and shorter process time in the manufacturing industry, higher cutting efficiency and machining of difficult-to-cut materials including cemented carbides has been increasing important.

Cemented carbides, first introduced in the 1923, are basically made of tungsten carbide(WC) with cobalt(Co) as the binders, are also known as normal tungsten carbides.

Other cemented carbides also contain titanium carbide(TiC), tantalum carbide(TaC), and niobium carbide(NbC) to improve crater-wear resistance and hot hardness. These are used for machining steels.[1,2]

Because of their high hardness over a wide range of temperature, high modulus of elasticity, high thermal conductivity, and low thermal expansion, their usage has been already broadened to every commercial application such as cutting tools, mining tools, and impact resistant tools, etc.

Crater-wear resistant cemented carbides contain more cobalt compared to normal tungsten carbides used

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for cutting tools, and the grain size of the tungsten carbide is larger.

This alloy is one of the most difficult-to-cut materials, but technological development is frequently attributed to availability of the machining of difficult-to-cut materials at present. The machining of cemented carbide is mainly dependent on the grinding process because milling, turning and drilling have many difficulties. And various grinding experiments on crater-wear resistant cemented carbides have been previously carried out in the author's previous work.[3,4,5,6,7,8]

Recently, PCD (Poly-Crystalline Diamond) and PCBN (Polycrystalline Cubic Boron Nitride) tools have been put into practical use, and the machining of the tungsten carbides is becoming gradually easier. Although there are several available technical reports regarding tool life, surface roughness and cutting force in longitudinal turning with crater-wear resistant cemented carbides, knowledge and technical data are limited and do not offer enough information to understand completely the mechanics of cutting yet.[9,10,11]

And so, this research describes that the cutting characteristics and the tool wear behavior in the micro cutting of three kinds of crater-wear resistant cemented carbides (WC-Co; V40, V50 and V60) using PCD (Poly Crystalline Diamond) and PCBN (Polycrystalline Cubic Boron Nitride) cutting tools in performance with SEM (Scanning Electron Microscope) direct observation method. Therefore, the purpose of this research is to present reasonable cutting conditions from the viewpoint of high efficient cutting refer to precise finished surface and tool wear.

2. Experimental device and procedure

2.1 Micro cutting device in SEM

The orthogonal micro cutting device for difficult-to-cut materials such as the tungsten carbides in SEM was developed for investigating the proposed method.

Fig. 1 shows the orthogonal micro cutting device in SEM developed for investigating the proposed method. Also, the structure of the micro cutting device in SEM is shown in Fig. 2.

This apparatus is composed mainly of the work material holder, the tool holder, and a specially designed strain gauge type tool dynamometer shown in Fig. 3.

As improved devices could move the work material holder directly using a motor, the correct depth of cut within 1μm could be obtained. By specifically improving the tension spring of the work material holder, the tensile load in the opposite direction of the cutting was restricted and the work material's transfer by cutting force could be stopped.

The tool holder was manufactured to change the height of the tool depending on the thickness of work material, as was the previous apparatus for fixed load. As tool holders have the highest stiffness, the flexure deformation could be repressed in the cutting of the cemented carbide.

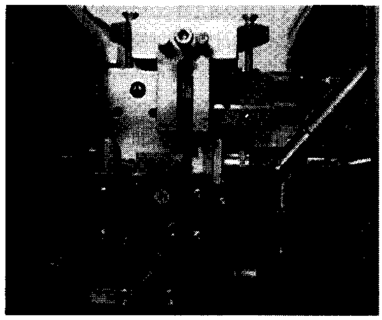
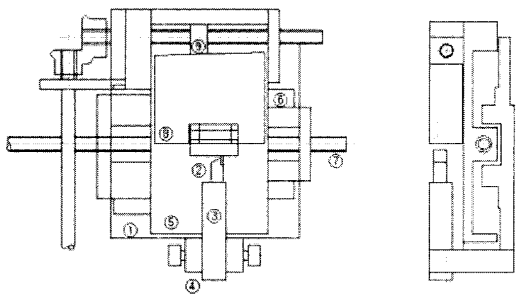


Fig. 1 Photo of micro cutting device in SEM



① base block ② tool ③ tool holder ④ tool post
⑤ work material base ⑥ rail block ⑦ ball screw
⑧ work material holder ⑨ feed apparatus

Fig. 2 Structure of micro cutting device

2.2 Work material/Tool materials and experimental condition

The work materials are V40, V50 and V60 grade tungsten carbide that are used mainly for crater-wear resistant cemented carbides in metal mould factories.

The chemical compositions are shown in Table 1. The mechanical and the thermal properties of this work material are shown in Table 2. As shown in Table 2, the values of hardness and Young' s modulus become lower as the quantity of cobalt increases. This work material was sintered and formed to the designated size (15×15×0.7mm), and lapped after being ground on a precision grinding machining.

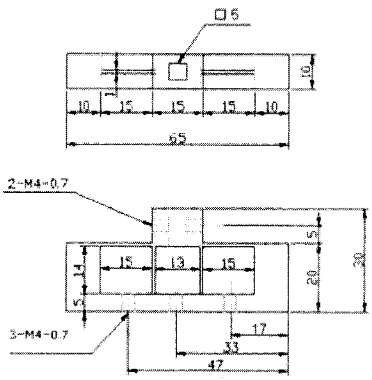


Fig. 3 Tool dynamometer for micro cutting

Table 1 Chemical composition(wt%)

Cemented carbides	W	Co	Ti	Ta	C
V40	73.3~78.0	17~22	-	-	4.7~5.1
V50	73.3~78.0	17~22	-	-	4.7~5.1
V60	65.3~73.7	22~30	-	-	4.3~4.7

Table 2 Mechanical properties

Cemented carbides	Hardness (Hv)	Compressive strength (kg/mm^2)	Young's modulus (×10^4 kg/mm^2)
V40	86.5	420	5.4
V50	84.0	360	5.1
V60	82.0	320	4.8

The work material fixed on the micro cutting device was cut after confirming that pressure in the vacuum chamber reached 2.0×10^{-2} Pa in SEM. During the micro cutting, the cutting was stopped and a photo was taken. The micro cutting tool materials used for this experiment were PCD and PCBN cutting tools. The PCD cutting tool used has three kinds of tool geometries with the front rake angle α of 0° and the relief angle β of 3°. On the other hand, the PCBN cutting tool used only has the front rake angle α of 0° and the relief angle β of 3°. In these cutting conditions, the cutting speed was 2, 10, and 100μm/s, and the depth of cut was approximately 5 and 20μm.

The first observation of the work material focused on experimental cutting and was carried out with SEM direct observation after micro cutting at the depth of cut of 10μm. More detailed tool geometry and cutting conditions are shown in Table 3.

Table 3 Experimental conditions of micro cutting

Cutting speed v(μm/s)	2, 10, 100
Depth of cut t(μm)	5, 20
Tool material, rake angle(α) and flank angle(β)	PCD α= 0°, − 5°, 12° β= 3°, 6° PCBN α= 0°, β= 3°

3. Result and Discussions

3.1 Machining characteristics by cutting resistance

In order to find out the microstructure of the used work material V60 composition, the SEM observation was carried out before experiment shown in Fig. 4. In this figure, dark part shows WC particles and gray part shows Co as the binders. It can be seen that the WC particle's size is about 5μm~10μm.

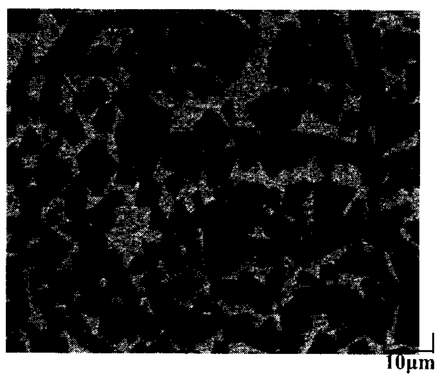


Fig. 4 Microstructure of used work material V60 composition

3.1.1 Cutting resistance according to weight percentage of WC

Fig. 5~Fig. 8 show the relation between weight percentage (wt%) of WC and cutting resistance in the micro cutting of the crater-wear resistant cemented carbides with the PCD tool at the depth of cut of 5, 20μm and the cutting speed of 2, 10 and 100μm/s.

As seen in Fig. 5 and 6, in the PCD tool changed with the front rake angle α of 0°, -5° and the relief angle β of 3° at the depth of cut of 5μm, the cutting resistance increased slightly as the increase in the weight percentage of WC.

However the change of the thrust cutting force was shown to be different from the principal cutting force regarding weight percentage of WC. Observing the increasing tendency, we see that cutting force for V50 is higher than one for any other work materials.

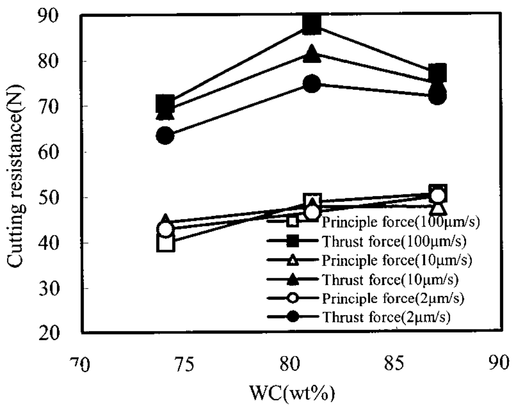


Fig. 5 Comparison of cutting resistances according to weight percentage (wt%) of WC
[Tool; PCD α=0°, β=3°, t=5μm]

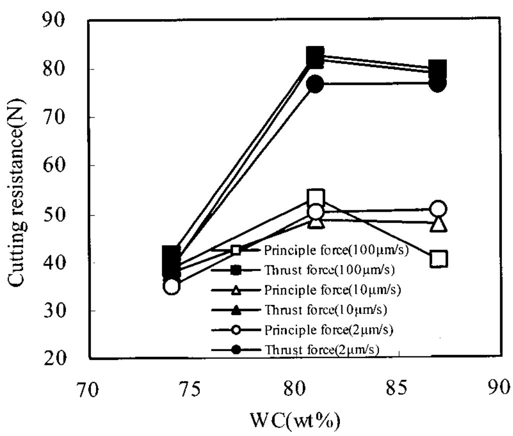


Fig. 6 Comparison of cutting resistances according to weight percentage (wt%) of WC
[Tool; PCD α=− 5°, β=3°, t=5μm]

Fig. 7~Fig. 8 show the cutting resistance against weight percentage of WC when using a PCD tool changed with the front rake angle α of 0°, -5° at the depth of cut of 20μm in the micro cutting.

In Fig. 7~ Fig. 8, the same trend was observed as the previous condition such as the depth of cut of 5μm, the principal force increased slightly as the increase of the weight percentage of WC. But the thrust cutting force did not change significantly within this experimental range.

However, it can be said that the weight percentage of WC influenced the thrust force, and the cutting resistances was increased proportionally to the weight percentage of WC shown in Fig. 5 and 6, too.

Considering the cutting of tungsten carbide, in this experiment, the cutting resistances were different from ordinary cutting such as cutting of steel or cast iron.

Those large values were obtained by order of thrust force, principal force, and a peculiar phenomenon said to be one feature of cutting high strength materials such as cemented carbide.

Finally, in case of the same types of experimented tools at the depth of cut of 20μm, cutting resistance has been shown to be significantly different from the case of tool geometry mentioned above. So, when using the tool with the front rake angle α of -5°, the cutting resistance tends to increase more as the weight percentage of WC is increased than using the tool with the front rake angle α of 0°.

It can be considered that the WC particles hardly influenced the cutting resistance when using the tool with the front rake angle α of -5°, because of the depth of cut is deeper than the size of WC particles in micro cutting in SEM.

And also, it seemed that many WC particles in this work material play an important role in the change of cutting characteristics. For xample, the cutting resistance might be more increased as the cutting tool pass the region where there are many WC particles within the work material according to the cutting process from the view point of above results.

3.1.2 Cutting resistance according to cutting speed

Fig. 9~Fig. 10 shows the relation between the cutting resistance and the cutting speed at the depth of cut of

5μm and 20μm when using a PCD tool with the front rake angle α of 0° in the micro cutting in SEM.

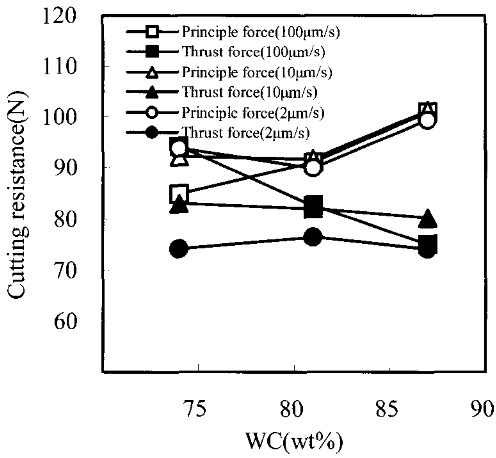


Fig. 7 Comparison of cutting resistances according to weight percentage (wt%) of WC [Tool; PCD α=0°, β=3°, t=20μm]

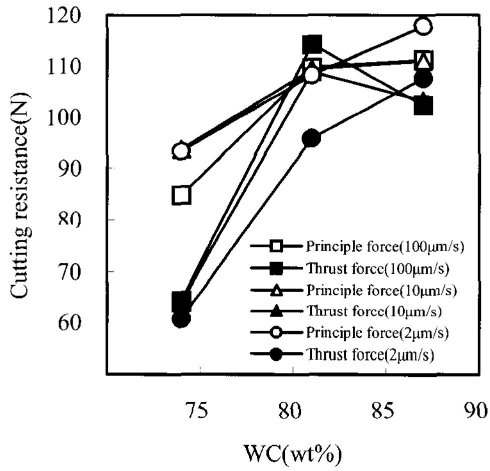


Fig. 8 Comparison of cutting resistances according to weight percentage (wt%) of WC [Tool; PCD α=−5°, β=3°, t=20μm]

At both depths of cut, the cutting speed dose not have an effect on the principal force so much within this experimental conditions. The thrust force increased slightly as the increase of the cutting speed. The tendency of increase of the thrust force was obviously observed specially at the low cutting speed region.

It implies that the increase of the thrust force is influenced by the frictional force on the rake face of tool and/or by friction between the cutting tool edge and the WC particles. It seems that friction may be ignored at the ultra low cutting speed such as 2m/s.

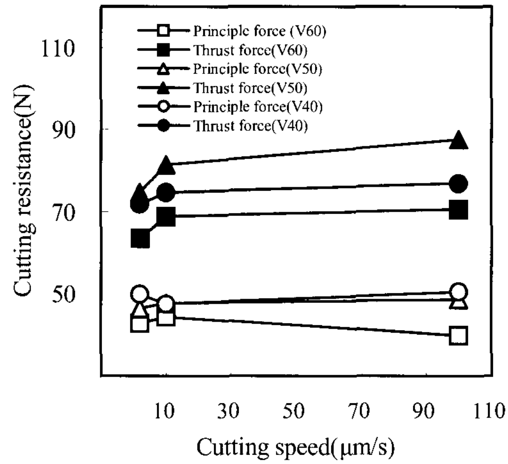


Fig. 9 Comparison of cutting resistances according to cutting speed [Tool; PCD α=0°, β=3°, t=5μm]

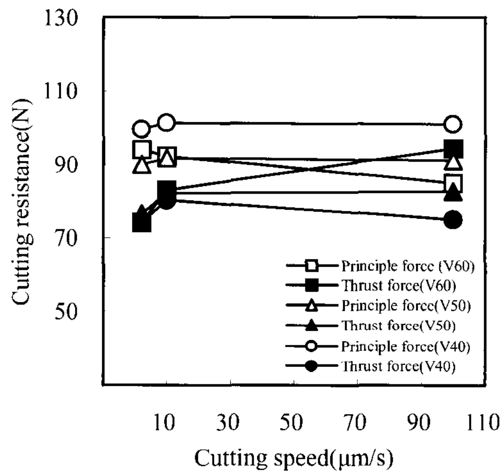


Fig. 10 Comparison of cutting resistances according to cutting speed [Tool; PCD α=0°, β=3°, t=20μm]

3.1.3 Cutting resistance according to depth of cut

Fig. 11~Fig. 12 shows the relation between the cutting resistance and the depth of cut at the same cutting speed of 10μm/s when using a PCD tool changed with the front rake angle α of 0°, -5° in the micro cutting in SEM.

As expected commonly in the case of cutting of difficult-to-cut materials, the thrust cutting force increased with the depth of cut in the range of the small depth of cut.

As not expected, however, it can be seen that the principal cutting force grew more than the thrust cutting force at the depth of cut of 20μm. It is notable in Fig. 11~Fig. 12 that the principal cutting force is due to the effect of the large size WC particle which existed atypically in the microstructure.

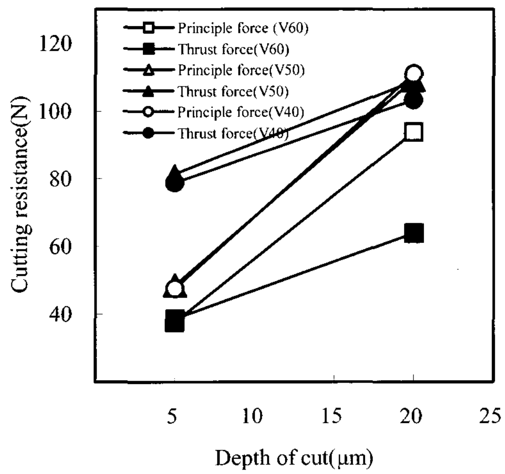


Fig. 11 Comparison of cutting resistances according to depth of cut [Tool; PCD α=0°, β=3°, t=10μm]

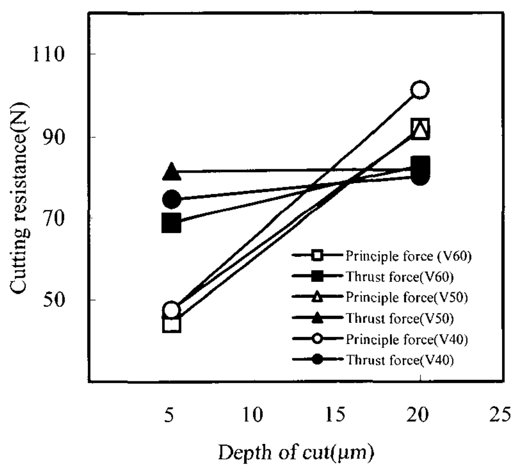
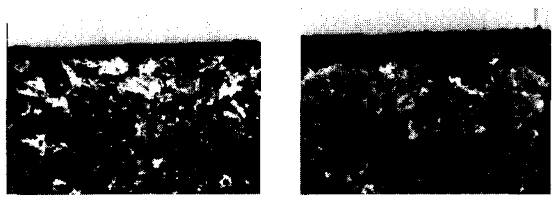


Fig. 12 Comparison of cutting resistances according to depth of cut [Tool; PCD α=− 5°, β=3°, t=10μm]

3.2 Tool wear

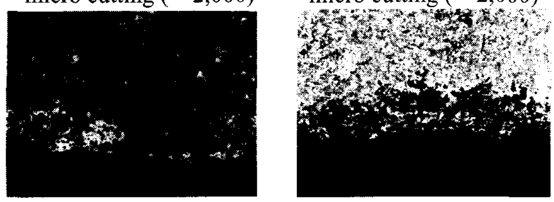
Fig. 13 shows the SEM photographs of tool wear shape on rake and flank faces of the PCD tool with the positive front rake angle α of 12° and the relief angle β of 6° on the micro cutting of crater-wear resistant cemented carbides V60. In this figures, (a) and (c) show tool shapes before cutting and (b) and (d) show the tool wear shapes after 30mm cutting distance. As can be clearly seen in (b) and (d), the tool wear formed on the rake and flank faces.

From the results of these SEM observations, the wear type of the PCD tools is shown to be abrasion by hard WC particles of the work materials, which lead diamond grain to be detached from the bond. It seems that the WC particles are broken and come into contact with the tool edge directly. This causes tool wear, resulting in significant tool scrape



(a) rake face before micro cutting (× 2,000)

(b) rake face after micro cutting (× 2,000)



(c) flank face before micro cutting (× 2,000)

(d) flank face after micro cutting (× 2,000)

Fig. 13 SEM photographs of tool wear shape on rake and flank face of PCD tool in micro cutting of WC-Co V60 after 30mm cutting distance [v=10μm/s, t=10μm, α=12°, β=6°]

Fig. 14 (a)~(d) illustrate atypical failure of PCD and PCBN tool with the front rake angle of 0°. In this figure, the left hand side of the same figure shows a PCD tool, and the right hand side shows the PCBN tool.

In the orthogonal micro cutting of crater-wear resistant cemented carbides, the tool failure in the flank face was formed bigger than that in the rake face on orthogonal micro cutting.

By the way, a large end tool wear are observed to the PCBN tool. The end tool wear is an undesirable tendency for the surface integrity.

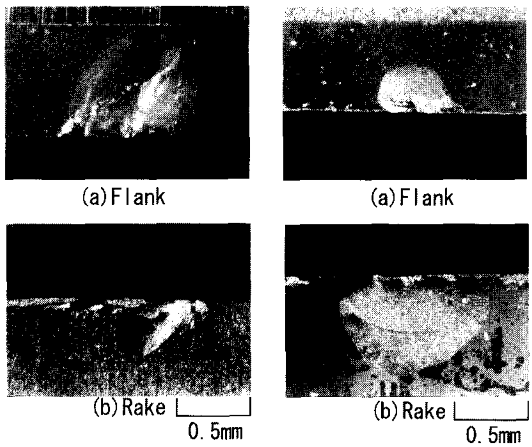


Fig. 14 Optical microphotographs of typical chipping

3.3 Machined surface integrity

In the cutting of brittle materials, chips are produced by the cracks owing to the concentrated stress at the cutting edge contact. Then, the tool geometric shapes will be very important.

Fig. 15 shows the SEM photograph of the machined surface integrity which is formed by micro cutting of crater-wear resistant cemented carbides V60 with various changed tool geometric shapes such as PCD with the front rake angle α of positive (α=12°), 0°, negative (-5°) and PCBN with the front rake angle α of 0°.

In Fig. 8 (a)~(c), parallel and irregular grooves which are lying in the longitudinal direction could be observed to grow up with increase of the positive rake angle. This suggests that the elastic deformation underneath the tool flank increases with the negative angle.

On the other hand, in case of cutting with a PCBN tool, some flaky pieces of irregularity with a deep crack are obviously observed shown in Fig. 8 (d).

From these results, the PCD tool with the negative positive front rake angle such as 0° and -5° is suitable for machining of crater-wear resistant cemented carbides.

However an extremely negative angle is unfavorable because it causes very poor surface integrity produced by the major cutting edge.

And the machined surface integrity on the side of cutting tool with a negative rake angle was better than that with positive one, as well as the burr formation using the cutting tool with a negative rake angle showed far less formed compared to the that with a positive one shown in Fig. 16.

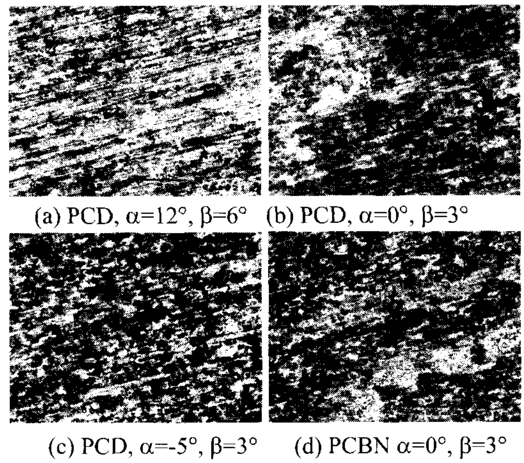


Fig. 15 SEM photograph of the machined surface integrity by various tool shapes [WC-Co V60, v=10μm/s, t=10μm, ×500]

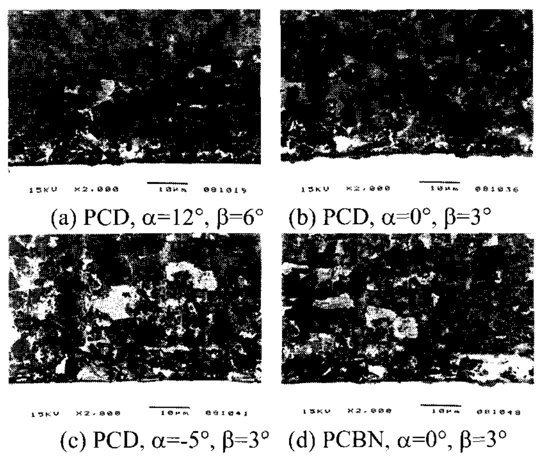


Fig. 16 SEM photographs of cutting surface in the side view by various tool shape [WC-Co V60, v=10μm/s t=10μm, ×2,000]

4. Conclusions

This research describes that the cutting characteristics and the tool wear behavior in the micro cutting of three kinds of wear resistant WC-Co(V40, V50 and V60) using PCD (Poly Crystalline Diamond) and PCBN (Polycrystalline Cubic Boron Nitride) cutting tools in performance with an SEM (Scanning Electron Microscope) direct observation method. The purpose of this research is to present reasonable cutting conditions from the viewpoint of high efficient cutting refer to precise finished surface and tool wear. Summary of the results are shown below:

1. The cutting forces tend to increase as the increase of the weight percentage (wt%) of WC particles, and the thrust force was larger than the principal force in the cutting of WC-Co. These phenomena were different in balance from the ordinary cutting such as that cutting of steel or cast iron.
2. The cutting speed hardly influenced the thrust force, because of the frictional force between the cutting tool edge and small WC particles at the low cutting speed region such as 2μm/s in micro cutting in SEM. It seemed that the thrust cutting force occurred by the contact between the flank face and work material near the cutting edge.
3. The wear type of the PCD tools is shown to be abrasion by hard WC particles of the work materials, which leads diamond grain to be detached from the bond.
4. From the SEM direct observation in cutting the WC-Co, it seems that WC particles are broken and come into contact with the tool edge directly. This causes tool wear, resulting in significant tool scrape.
5. In the orthogonal micro cutting of WC-Co, The tool wear in the flank face was formed bigger than that in the rake face in orthogonal micro cutting. And the machining surface integrity on the side of cutting tool with a negative rake angle was better than that with positive one, as well as burr in the case of using the cutting tool with a negative rake angle was formed very little compared to the that with a positive one

References

1. Suzuki, H., "Cemented Carbides and Sintered Hard Materials," Maruzen Co. Ltd., p. 33, 1989.
2. Serope, K., "Manufacturing processes for engineering Materials," Addison-Wesley Publishing Co., p.525, 1984.
3. Heo, S. J., Kang, J. H., Kim, W. I., "Study on Ultra-Precision Grinding Condition of WC-Co," KSPE, Vol. 10, No. 1, pp. 42-51, 1993.
4. Heo, S. J., Kang, J. H., Kim, W. I., "A Study on the High Efficiency Grinding of WC-Co," KSME(A), Vol. 17, No. 3, pp. 721-730, 1993.
5. Heo, S. J., Wang, D. H., Kim, W. I., "Surface Grinding of Tungsten Carbide for High Quality Using Diamond Wheel," Transactions of the KSMTE, Vol. 4, No. 3, pp. 12-24, 1995.
6. Heo, S. J., "A Study on the Internal Grinding of Tungsten Carbide Materials to Improve the Machining Performance," KSPE, Vol. 13, No. 6, pp. 52-58, 1996.
7. Heo, S. J., Kang, J. H., Kim, W. I., "A Study on the High Efficiency Grinding of WC-Co," KSME(A), Vol. 17, No. 3, 721-730, 1993.
8. Heo, S. J., Kang, J. H., Kim, W. I., "A Study on the Grinding of WC-Co with High Quality," The 1st ABTEC, 1993.
9. Technical Research Institute, Japan Society for the Promotion of Machine Industry, Machining Data Files, Tokyo, Japan, 95-0323, 1997.
10. Technical Research Institute, Japan Society for the Promotion of Machine Industry, Machining Data Files, Tokyo, Japan, 95-0325, 1997.
11. Technical Research Institute, Japan Society for the Promotion of Machine Industry, Machining Data Files, Tokyo, Japan, 92-0298, 1995.