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Environmentally conscious hard turning of cemented carbide materials on the basis of micro-cutting in SEM: stressing four kinds of cemented carbides with PCD tools

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Abstract

Environmentally conscious hard turning and technology has placed more importance on the machining process. In this research, the possibility of environmentally conscious hard turning of cemented carbides was studied. The effects of cutting methods of dry and wet (vegetable oil mist, and mineral oil) and work material on cutting resistance and wear characteristics of cutting tools were experimentally investigated. The turning and micro-cutting process in SEM was carried out by using four kinds of tungsten carbides with the PCD cutting tools. Specifically, an emphasis was put on the effect of WC and Co additives in four kinds of cemented carbides on machinability and tool wear characteristics. The tool wear width and the cutting resistances were measured, and the worn flank was observed..

Keywords: Environmentally conscious hard turning; Micro-cutting in SEM; Cemented carbide materials; PCD cutting tool; Wear characteristics of cutting tools; Cutting resistance

1. Introduction

Many environmental concerns have been raised in the advent of machine technology. Since cutting fluid has a huge ecological impact, much research is being carried out to minimize the use of cutting fluids. However, tool wear is very severe in hard turning cemented carbide materials without cutting fluid.

Cemented carbides consist of hard particles (WC, TiC, TaC, etc) and metallic binders, and they are manufactured by using the powder metallurgy method. Because of their high hardness over a wide range of temperatures, 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 resistance tools. Crater-wear resistant cemented carbides contain more cobalt compared to normal tungsten carbides used for cutting tools, and the grain size of the tungsten carbide is larger.

They are occasionally ground and machined for the finishing process. However, it is well known that cemented carbides are difficult to cut materials and the tool wear is very severe in cutting with the PCD tool; the cost of production also becomes high. [1-5]

In a previous study, the turning [6] and the micro cutting in the SEM (Scanning Electron Microscope) [7-12] were carried out to clarify the tool wear mechanism. In the cutting of the cemented carbides, the thrust forces became bigger than the principal and feed forces, and the relation between the tool wear and the cutting forces was clarified.

Moreover, in the micro cutting test, the behavior of WC particles was observed in the deformation zone around the cutting edge in detail. Though it is supposed that the cutting mechanism differs by the influence of WC and Co content in cemented carbides, there is little research about the influence of WC and Co content.

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Therefore, in this study, the turning and micro-cutting process in SEM was carried out by using three kinds of tungsten carbides with the PCD cutting tools. Special emphasis was put on the effect of WC and Co additives in three kinds of cemented carbides on machinability and tool wear characteristics. The tool wear width and the cutting forces were measured, and the worn flank was observed. Therefore, the purpose of this research was to study the possibility of environmentally conscious hard turning of cemented carbides from the viewpoint of high efficiency cutting and precise finished surface and low tool wear.

2. Experimental device and procedure

2.1 Micro cutting device in SEM

An 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. As improved devices could move the work material holder directly by using a stepping motor, the correct depth of cut within 0.1μm could be obtained. By specifically improving the rack and pinion adjustment 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 the 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.

This work material involved V40, V50 and V60 grade tungsten carbides which were sintered and formed to the designated size (15 × 15 × 0.7mm), and lapped after being ground on a precision grinding machining. 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 the image was captured on camera. The micro cutting tool materials used for this experiment were PCD cutting tools. The PCD cutting tool geometries with the front rake angle measured α of 0° and the relief angle β of 3°.

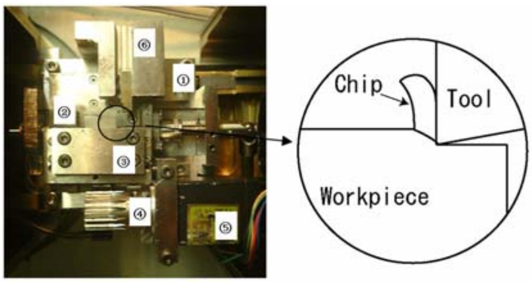


Fig. 1. Micro cutting device in SEM and schematic illustration of in-situ observation ① base block ② work material base ③ work material holder ④rack and pinion adjustment ⑤ stepping motor(0.0036°/step) ⑥ tool holder.

The first observation of the work material focused on experimental cutting and was carried out with SEM direct observation after micro cutting at a depth of cut of 10μm. More detailed tool geometry and cutting conditions are shown in Table 1.

2.2 Turning experiment

The cutting test was carried out with the CNC lathe with a Sentrol-L system. The cylindrical turning conditions are shown in Table 2. The cutting speed was 15m/min, the feed rate was 0.1mm/rev and the depth of cut was 0.1mm. The cutting methods were dry, mist and wet.

Table 1. Experimental conditions of micro-cutting.

Work material	V40, V50, V60
Cutting speed v(μm/s)	5, 10, 100
Depth of cut t(μm)	2, 5, 10, 20, 30, 40
Tool material,	PCD
Tool geometry	rake angle α= 0°, flank angle β= 3°
Cutting method	Dry, Wet

Table 2. Cylindrical turning conditions.

Work material	V30, V40, V50, V60
Cutting speed [m/min]	15
Feed rate [mm/rev]	0.1
Depth of cut [mm]	0.1
Tool configuration	(-5, -5, 5, 5, 30, 0, 0.8)
Cutting method	Dry Wet (Mobil Sultran B3 : 150ml/min) Mist (Bluebe : 55ml/h, Water : 194ml/h)

Table 3. Chemical compositions of cemented carbides (wt%).

Cemented Carbide	WC	Co
V30	90	10
V40	87	13
V50	81	19
V60	75	25

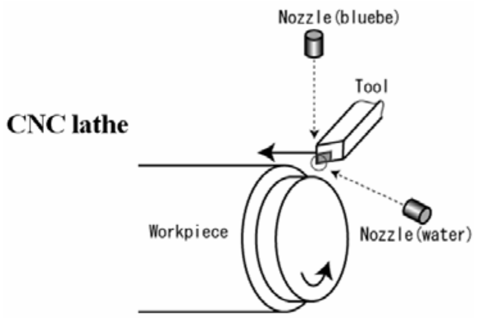


Fig. 2. Method of supplying oil and water mist.

The PCD tool was used. The cutting tool geometry is (-5, -5, 5, 5, 30, 0, 0.8) and the tool material is the PCD. The tool wear width was measured, and the worn tool and the surface roughness of the work were observed at 40m cutting distance. When the tool wear width became more than 0.3mm, the cutting test was stopped. The mechanical properties are shown in Table 3.

The cutting methods, wet (Mobil Sultran B3), and mist (Bluebe). Fig. 2 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 worn tool was observed with an optical microscope at every 40m cutting distance.

2.3 Work material/Tool material

The work materials were four cemented carbides (V30, V40, V50 and V60 grade) that are mainly used for wear and impact resistant tools in metal mold factories. Their chemical compositions are shown in Table 3. In this table, they consist of WC and Co, but V30, V40, V50 and V60 grade of the cemented carbides have different ratios of WC and Co. As the number increases, the more the Co content increases.

Their mechanical properties are shown in Table 4. The value of hardness, compressive strength and Young's modulus are low according as the quantity of Co increases.

Table 4. Mechanical properties of cemented carbides.

Cemented carbide	Specific gravity [Mg/m^3]	Hard-ness [HRA]	Compressive strength [GPa]	Young's modulus [GPa]
V30	14.4	88.5	4.61	578
V40	14.1	86.0	4.12	540
V50	13.5	84.0	3.53	500
V60	13.1	82.0	3.14	470

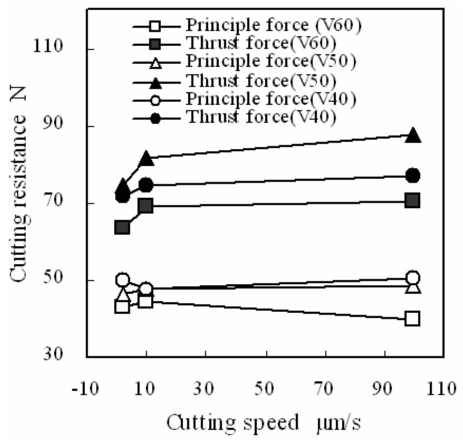


Fig. 3. Comparison of cutting resistances according to cutting speed [Tool; PCD α=0°, β=3°, t=5μm, Dry].

The WC particle diameter of the V40, V50 and V60 cemented carbides is rough and large, but that of the V30 shows a fine grain size. The Co area of the V60 cemented carbide is the largest measured.

3. Resulnd discussion

3.1 Micro cutting experiment in SEM

3.1.1 Cutting resistance according to cutting speed

Fig. 3-Fig. 4 show the relation between the cutting resistance and the cutting speed in dry cutting at a depth of cut of 5μm and 20μm when using a PCD tool with the front rake angle α of 0°. At both depths of cut, the cutting speed does not have much of an effect on the principal force within these experimental conditions. The thrust force increases slightly as the cutting speed increases. The tendency of the thrust force to increase was observed more clearly 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 an ultra low cutting speed

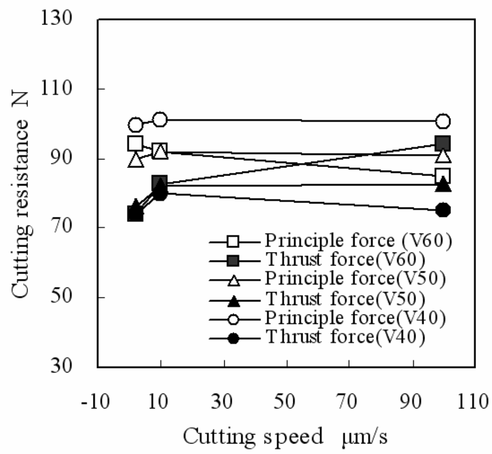


Fig. 4. Comparison of cutting resistances according to cutting speed [Tool; PCD α=0°, β=3°, t=20μm, Dry].

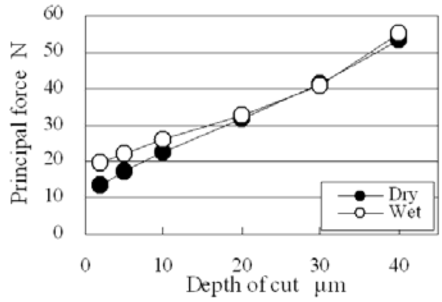
such as 2m/s.

3.1.2 Cutting resistance according to depth of cut

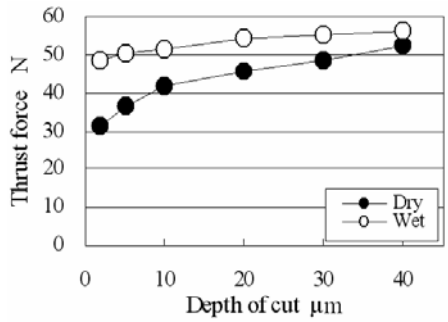
The orthogonal micro cutting was carried out in dry and wet cutting conditions. Fig. 5 shows the relation between the depth of cut and the two cutting resistance parameters, principal force and thrust force at the same cutting speed of 100μm/s. In this figure, the left hand side of the same figure shows a principal force, and the right hand side shows the thrust force. As expected in the case of cutting of difficult-to-cut materials, the thrust cutting force increases with the depth in the range of the small depth of cut. This increasing tendency of cutting resistances at the primary cutting region is the same as the experimental result that was obtained for the cylindrical turning in the Fig. 13 of section 3.2.4 below.

However the change of the thrust cutting force is shown to be different from the principal cutting force regarding cutting method. In Fig. 5(a), the principal force linearly increases with the depth of cut both in the dry and wet cutting.

In dry cutting, the thrust cutting force linearly increases with the depth of cut, but there is no significant difference in wet cutting. As we know, the thrust cutting force was generated by the contact between the flank face and work material near the cutting edge. The flank wear did not increase so much at the primary cutting region when using a PCD cutting tool with the specific rake angle of 0 degrees. It is observed in Fig. 5(b) that the depth of cut effectively influences the cutting resistance in the wet cutting process. The explanation for this phenomenon is attributed to differences of tool wear shapes caused by the cutting methods.



(a) Principal force



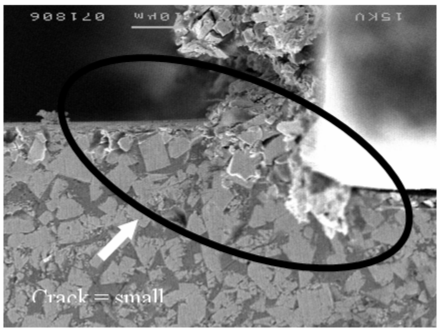
(b) Thrust force

Fig. 5. Relation between cutting resistance and depth of cut [V = 100μm/s].

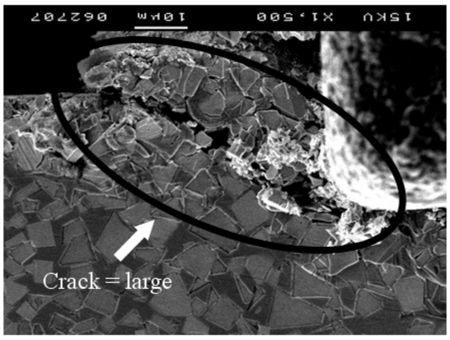
3.1.3 SEM direct observation of micro cutting of cemented carbide

Fig. 6 shows typical SEM photographs of the machined region at a point 200μm after dry cutting. In this figure, the left hand side of the same figure formed a cut with a depth of 10μm, and the right hand side formed a cut with a depth of cut of 20μm at the same cutting speed of 100μm/s. From the SEM direct observation of micro cutting, primary WC particles were crushed and/or transformed into the grains in the shearing deformation zone. Some of them were observed to collide directly with the cutting edge of the tool as the micro-cutting continued. This appears to be the cause of severe tool wear in turning the cemented carbides. The micro-cutting continued, and the chip formed into the discontinuous type as shown in Fig. 6.

Also, from these photographs, a shearing deformation zone appearing upward at a slant could be seen. The WC particles on the shearing deformation zone are broken severely.



(a) t=10μm



(b) t=20μm

Fig. 6. Typical SEM photographs [V=100μm/s, Dry].

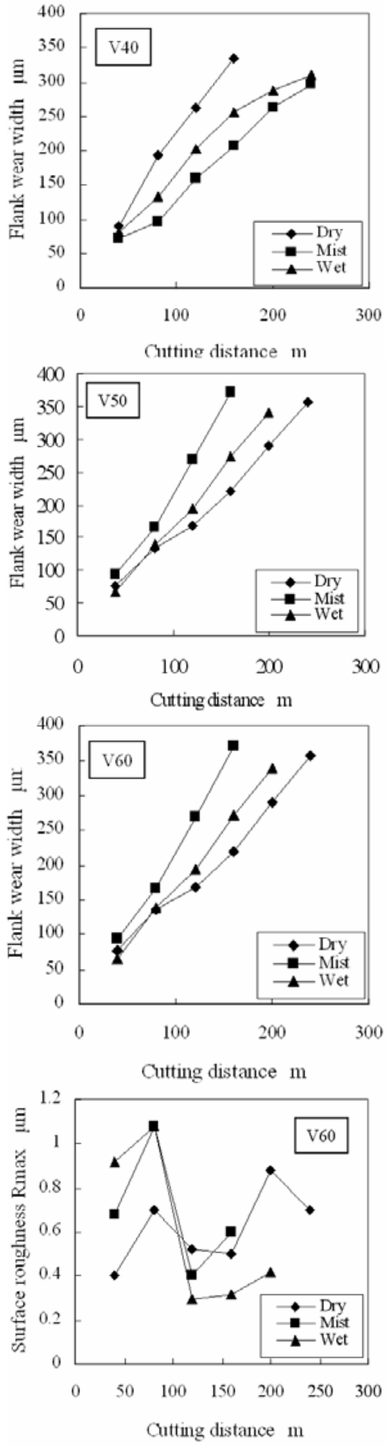
Fig. 6 shows that there are two crack formation types. One type of shear angle is comparatively small and the small crack of the shear plane does not widen; the other is a type of shear angle above 45 degrees and the large crack of the shear plane widens. These differences are caused by the stress condition, which gives rise to the friction at the shear plane.

Observing this crack tendency, the tool wear decreased due to sufficient lubrication between the work piece and the flank in mist or wet cutting. This cutting method has a cooling effect using the vegetable oil mist and cutting fluid. It is observed in Fig. 6 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 Turning experiment

3.2.1 Flank wear width

In order to achieve a systematic understanding of machining characteristics of cutting and tools in the environmentally conscious hard turning of cemented carbide materials, the work investigates experimentally the degree of tool wear, cutting resistance and surface roughness in relation to cutting methods.



[V=15m/min, f=0.1mm/rev, t=0.1mm]

Fig. 7. Relation between flank wear width and cutting distance, and surface roughness.

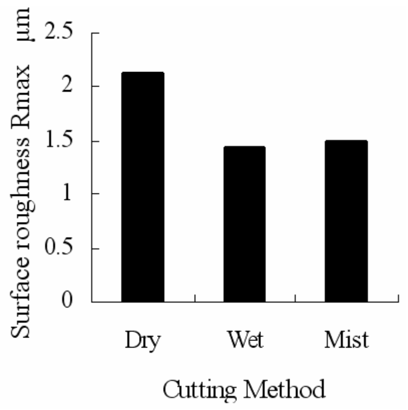


Fig. 8. Effect of cutting method on the surface roughness.

Fig. 7 shows the relation between the flank wear width, the cutting distance and the surface roughness. The tool life criterion was defined when the flank wear width was more than 0.3mm. The flank wear width of every tool material increased in proportion to the cutting distance. In cutting V40, the dry cutting makes the shortest tool life. In cutting V50, the wet cutting makes the shortest tool life. In cutting V60, the mist cutting results in the shortest tool life. It is thought that the higher the WC particle content, the more effective the mist or wet cutting.

On the other hand, Fig. 8 shows the effect of cutting method on the Rmax surface roughness parameter with cutting length of 280m. The work material is V30. Among the three cutting methods the wet cutting method resulted in the best surface roughness of 1.4μm and the roughness of the mist cutting was slightly higher.

Fig. 9 shows the relation between the flank wear width and the cutting distance. The tool life criterion was defined as the point when the flank wear width was more than 0.3mm. Among the cemented carbides whose binder was the Co, the tool life of the V60 was shortest, and it became long in the order of V40, V50, and V30. Because the values of the mechanical properties of the V30 were highest, this fact differs from the general theory that the larger the hardness measurement of the work material, the shorter the tool life.

The WC particle diameter of the V60 is largest. Though the WC particle diameter of the V40 is similar to the V50, the WC content of the V40 is more than the V50. As described above, it seems that the WC particle diameter influences the tool life greater than the WC content. Also, if the WC particle diameter is roughly the same, the WC content or the hardness of cemented carbide influences the tool life as the second factor.

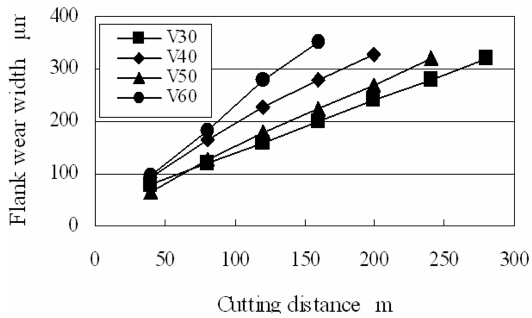
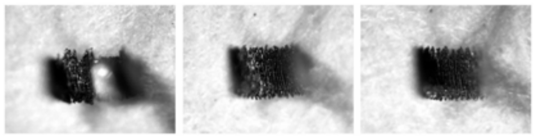
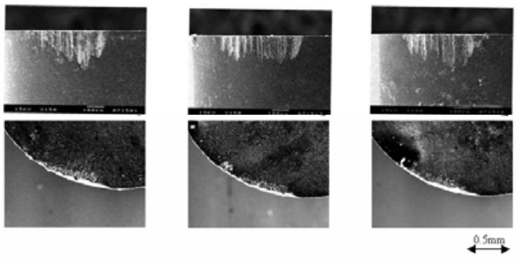


Fig. 9. Relation between flank wear width and cutting distance [Dry].



(a) V40 (b) V50 (c) V60

Fig. 10. Chip geometries in three work materials [Dry].



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

[V=15m/min, f=0.1mm/rev, t=0.1mm, L=280mm]

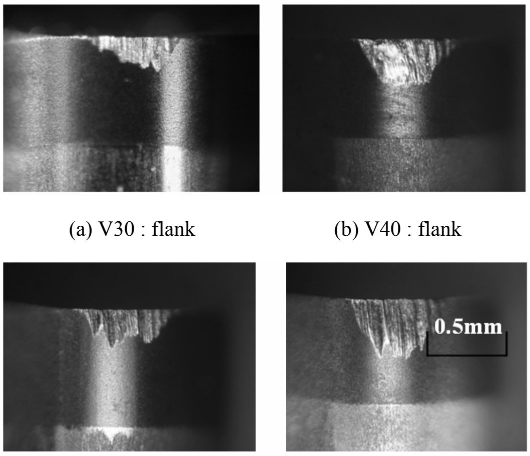
Fig. 11. SEM micrographs of tool in three cutting methods.

3.2.2 Chip geometry

Fig. 10 shows the shape of chips. It is shown that the edge of the chip is irregular in V40, and is long and thin in V60. The edge geometry of V50 is at the level intermediate between V40 and V60. The result follows the effect of the WC particle content.

3.2.3 Observation of worn tool

Fig. 11 shows photographs of the rake face and flank at 0.3mm flank wear width. The work material is V60. The wear shape in the dry cutting was similar to that in the wet cutting. Fig. 12 shows optical microphotographs of the flank and face of the worn tool at a



(a) V30 : flank (b) V40 : flank

(c) V50 : flank (d) V60 : flank

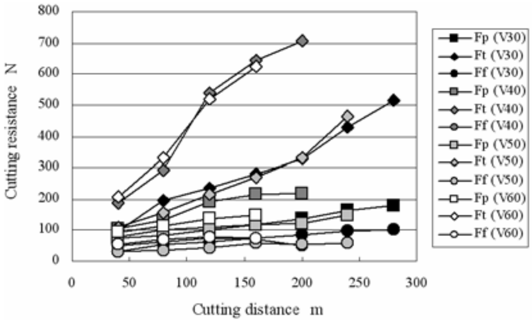
[V=15m/min, f=0.1mm/rev, t=0.1mm, L=160mm, Dry]

Fig. 12. Optical micro-photographs of insert.

cutting distance of 160 m. In the cutting of the V30, V40, V50 and V60, the face wear could be slightly observed though the micro-photographs could not be shown. As measured from Fig. 9 at the cutting distance of 160m, the flank wear widths of the V60, V40, V50 and V30 were 352, 280, 225 and 200μ m respectively. As shown in Fig. 12(d), it was clear that the flank wear of V60 was the largest.

3.2.4 Cutting resistance

Fig. 13 shows the relation between the cutting forces and the cutting distance in dry cutting. In this figure, the principal, thrust and feed forces are indicated as Fp, Ft and Ff, respectively. As can be seen in this figure, one can notice that this increasing tendency of the thrust cutting force is more evident than with the other cutting forces. It seems that the thrust forces were concerned with the flank wear. This may indicate the relation with the flank tool wear width closely, as the above mentioned shown in Figs. 11 and 12 of section 3.2.3 above. Though the value of the principal and feed forces differed a little among all cemented carbides, the same tendency was shown in micro cutting experimentation. The thrust forces in cutting of the V60 and V40 were large. The reason why the thrust force becomes large is that the large WC particle creates a strong contact point with the cutting edge [7], and it is thought that the main cause of the flank wear is abrasiveness in this case.



[V=15m/min, f=0.1mm/rev, t=0.1mm, Dry]

Fig. 13. Relation between cutting resistance and cutting distance.

4. Conclusions

The hard turning tests of four kinds of cemented carbides were carried out with the PCD tool in three cutting methods (dry, wet and mist) to investigate the possibility of environmentally conscious hard turning and the influence of WC and binders. From the result, the possibility of environmentally conscious hard turning of cemented carbides was observed. The main results obtained are as follows.

(1) In dry cutting of cemented carbide materials, the cutting force linearly increases, but there is no great difference in wet cutting. In mist cutting of cemented carbides, the more the WC was included, the longer the tool life became.

(2) The wet cutting method resulted in better surface roughness and was finest among the three cutting methods, whereas it was almost similar to that in the mist cutting.

(3) The tool wear did not always increase with an increase of the Co content. Not only the WC content but also the WC particle diameter influenced the tool life.

(4) The more the WC was measured, the more chip shape irregularities were found.

Aknowlegement

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