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〈論　文〉

A Study on the Machinability of Ceramics by Low Temperature Cooling Diamond Tool

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다이아몬드공구 내부 냉각법에 의한 세라믹스의 피삭성에 관한 연구

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요약—일반적으로 세라믹재료는 강도, 내식성, 내열성, 내마모성의 성질 등이 우수하여 신소재로서의 응용폭이 점점 확대되고 있으나, 가공성이 난삭재로 피삭성의 개발이 시급한 과제로 대두되고 있다.
본 연구에서는 가공 중 절삭열을 억제시키는 방안으로 극저온 내부 냉각공구시스템을 제작하고, 냉매로 액화질소를 순환 공급하면서 이때 난삭재인 세라믹 가공의 피삭성 향상의 가능성을 실험적으로 검토하였다.

1. Introduction

Ceramics is light and known to be excellent in wear resistance, thermal resistance and chemical stability. Its usefulness is being increased in using mechanical structure parts and electronic parts of electromagnetic features.

Especially, when using ceramics as mechanical structure parts, high accuracy and high efficiency processing must be accomplished with ceramics itself's trustness simultaneously[1].

For general ceramics process, diamond grinding wheel is generally used by selecting an appropriate one and establishing grinding condition but being limited in ecomonics, grinding efficiency and machining geometry[2, 3].

It is significant to investigate the possibility of cutting process with high process efficiency and high flexibility to accelerate the industrial application of ceramics.

For this field, the research is now an elementary step, so there are many factors to examine such as tool material, process condition and processing mechine etc, but from a tool quality point of view, many papers have insisted that diamond with high hardness and strength is most suitable[4-8]. But it is reported that high cutting temperature on diamond surface weaken the hardness and shorten the tool life. Therefore controlling cutting temperature is the most important problem[9-12].

So in this study to restraint cutting temperature during processing, low temperature cooling of internally diamond tool system is manufactured and circulating liquid nitrogen as a coolant and we examined the difficult-to-machine material, the machinability of ceramics process.

2. Experimental Apparatus & Method

Fig. 1 shows the Liquid Nitrogen Cooled Cutting Tool for experimentation. A discharger is installed on the vessel to supply liquid nitrogen and leading out reduced nitrogen 3.0 psi gas pressure to the liquid nitrogen vessel, which raises the internal pressure of the vessel and liquid nitrogen is supplied to the tool edge in liquid state through a ϕ 6 mm circulation pipe. To measure the cutting temperature, as Fig. 2 shows, a thermo-couple is installed on diamond tool surface with a hole of ϕ 1.1 mm made by an electric discharge. The K-type, thermo-couple is used to measure -270℃~1370℃. Fig. 3 represents the schematic diagram of Data Acquisition System for measuring cutting temperature. The thermo couple is attached to cutting test point of cutting tool, which connects with Reference Junction Thermo couple box of which outputs are used in conjunction with digital voltmeter through scanner and final outputs are inputted to HP computer and controlled by time-control. Hp computer converts them into temperature by using measured data of thermo couple which consists of two-section, precisely curve fitting, which are stored in disk driver and measured temperature output data are output by printer and plotter. Fine alumina, which is used for capstan consisted of Al_2O_3 96% and size ϕ 125 × ϕ 150 × 40, is used for the work piece and Table 1 shows chemical and physical properties of that.

Sintered diamond tool is the throw-away CNMG type and a diamond tip is attached on sintered carbide tool P20 with tool setting angle 0°, 0°, 5°, 5°, 15°, 15°, 0.8 and Table 2 shows the physical properties of tool. The cutting experiment is done by two methods. One is the case of cooling the tool edge and the other is executed in normal temperature.

CNC precision lathe (FANUC OT, KD) is used for this experiment, which has 7.5 KW main power and the cutting speed has in the range of 6-95 m/min using the control of constant cutting speed by the function of G96. The feed speed is 0.1 mm/rev and the external diameter is machined by a 0.3 mm depth of cut.

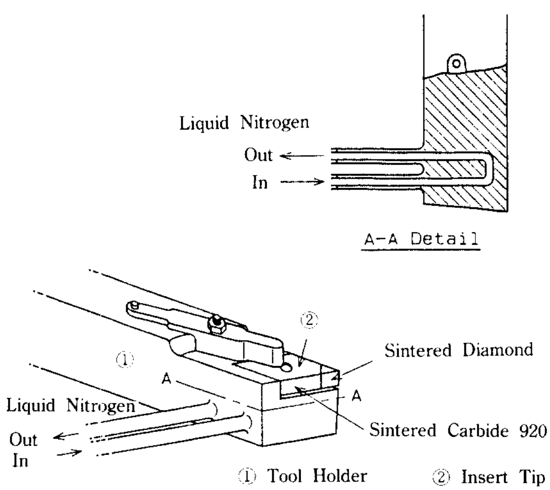


Fig. 1. Schematic illustration of liquid nitrogen cooled cutting tool type.

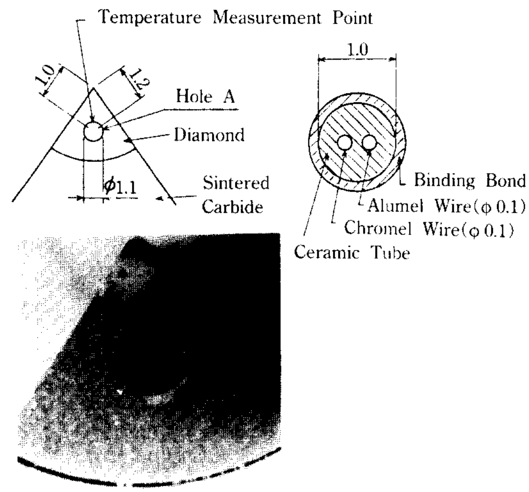


Fig. 2. Hole making for measuring temperature in diamond tool.

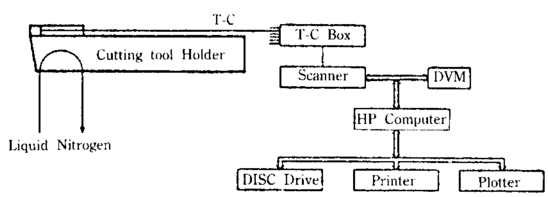


Fig. 3. Schematic diagram of the data acquisition system.

Table 1. Chemical and physical composition

Composition			Alumina Al_2O_3
Gas permeability			Impervious
Chemical composition	SiO_2	%	3
	Al_2O_3	%	96
	CaO	%	0.7
	MgO	%	0.3
Grain density (g/cm^3)			3.7
Color			White
Compressive strength (25°C) (kgf/cm^2)			21000
Flexural strength (kgf/cm^2)			3200
Tensile strength (kgf/cm^2)			1950
Hardness	Moh's scale		9
	Rock-w. 45 W		78
Thermal conductivity (400°C) (kcal/mh°C)			6.2
Grain size (μm)			5.0

Table 2. Physical properties of diamond tool

Abrasion resistance factor			250
Knoop Hardness (kg/mm^2)			7200
Diamond Grain			85%
Boundary			15%
	Cobalt		3%
	Void		4%
	Diamond bridge		8%
		Diamond	Cobalt
Young's modulus (TPa)		1.05	0.15
Grain size (μm)		8	6
Thermal conducitivity (w/mk)		1800	60
Coefficient of thermal elongation (l/k)		1.2×10^6	1.4×10^6
Thermal shear strength (GPa)		3.8	

The cutting resistance is measured by an AST type tool power gauge and the processed surface roughness is tested by profilometer record type of surface roughness tester and tool wear is measured by tool microscope (Carl Zeiss) and SEM (JEOL JSM 820). For this time the standard of frank surface wear width is observed by 0.3 mm. To photograph processed ceramics surface by SEM it is done by gold coatiog by 0.3 nm for 105 secs in state of vacuum (10^{-4} mbar/par) of SEM coating system machine manufactured by Bio Rad. For an accurate establishment of capstan ceramics work piece, a process of oil pressure chuck is need from time to time to raise the accuracy degree on a steady ceramics.

3. The Characteristics of Ceramics Cutting Tool

Generally, while the cutting pattern in a case of ductile and malleable metal is said to be the cutting tool of plasticity, macro fracture breaks out in hardened, brittle metal. Therefore inspecting the ceramics in a view of the pattern of cutting tool through linear fracture dynamics gives that while the depth of cutting is small, small-scaled fracture occurs when long, large- scaled fracture occurs.

Fig. 4 shows the pattern of ceramics cutting tool recorded by continuous observation of SEM. (1) is Primary crack formation, which is such a state that the limit of potential energy release rate (G) exceeds that of ceramics' (Gc), which is the condition of eq. (1) and there occurs crack forward from the tool edge.

$$G \geqq Gc \quad (1)$$

(2) is Primary crack arrest which is the case that the length of crack a increases together with G and crack continues to grow up in the condition of $dG/da \geqq 0$.

During this process, unstable materials are elimi-

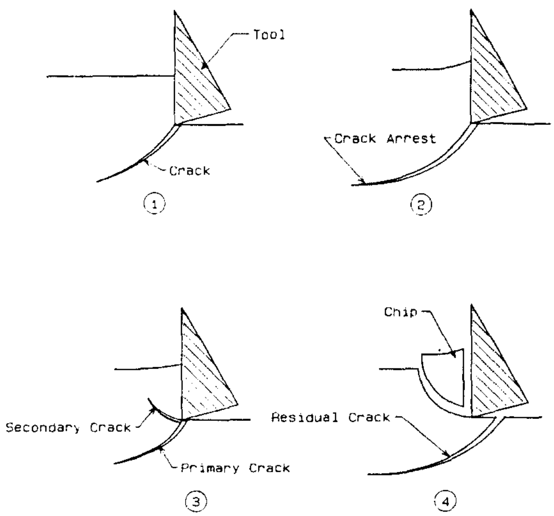
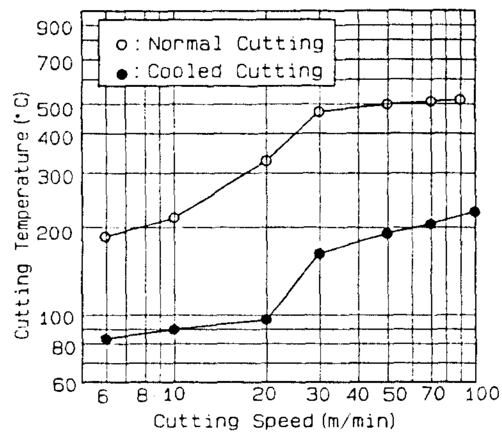


Fig. 4. Schematic illustration of mechanism of material removal process with residual crack[14].



Feed : 0.1 mm/rev

Depth of Cut : 0.3 mm/rev

Tool : Sintered Diamond(0,0,5,5,15,15,0.8)

Fig. 5. Relation of cutting speed and cutting temperature.

nated and especially in case of $dG/da < \mathbf{a}$, crack stops growing up being in the pattern of eq. 2 like (3) in the range of $G \geqq Ga$ and sequently crack remains in the finishing facet like (4).

$$G < Ga \qquad (2)$$

where Ga is crack of breaking toughness.

This crack progress is done faster than the feed rate of tool and in the case of cutting ceramics, crack progress always doesn't go through (2) (3), while going from (1) to (4). There is another case that it goes from (1) (2) to (4) or, from (1) abruptly to (4). Like this, if the materials above crack facet are eliminated rapidly, after process (1), macro crack does not excessively go toward lower direction but it is to get desired cutting surface. Also, if the process (1) of macro crack toward lower-forward direction occurs from the begining or stays in the small amount even if breaking up, it is to get more favorable cutting surface. Therefore diamond tool for manufacturing ceramics is said to imporve manufacturing process including imporvement of grade and cooling conditions of tool.

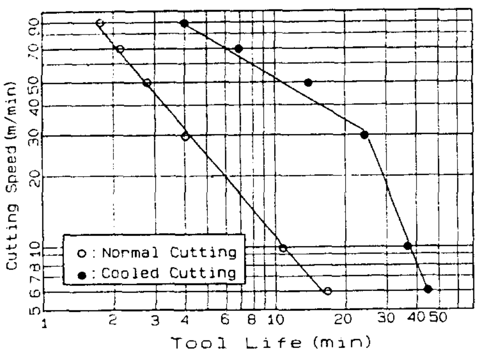
4. Results of experiment & Consideration

4.1 The relation between the ultimate-low cooling and cutting temperature

Fig. 5 shows the test result of cutting temperature of the sintered diamond tool which the locations been away by the distance 1.0 mm and 1.2 mm from the edge are measured by Alumel and Cromel thermocouple.

It is expected that like this experiment the measured result of the thermo-couple inserted method temperature will be somewhat lower than the defaced tool edge. But considering that the heat transfer rate of diamond is excellent, this data would be basic one in the trend analysis of either normal cutting or cooled cutting. In this point, the effect of cooled cutting is considerable and showing the great difference of temperature compared with normal cutting. By the way, the distribution of the cutting temperature has two regions, a low temperature region and a high temperature and it is observed that the boundary line is limited by the ranges from 20 m/min to 30 m/min.

The tool life in the standard of flank wear of cooled cutting state is compared with that of normal cutting on Fig. 6. Here, the Taylor formula of tool life fits well on normal cutting but on cooled cutting



Depth of Cut : 0.3 mm/rev, Feed : 0.1 mm/rev

Tool : Sintered Diamond Tool(0,0,5,5,15,15,0.8)

Fig. 6. Effect of cooled cutting upon tool life.

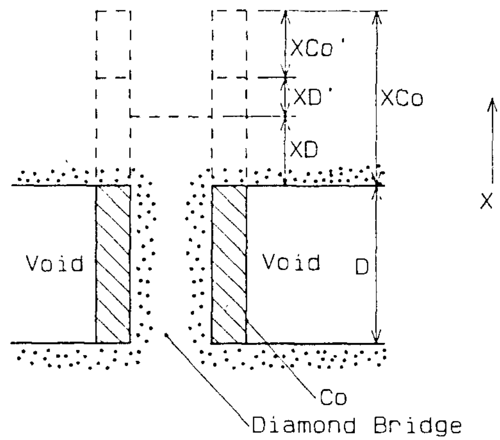


Fig. 7. Model of diamond bridge and cobalt[15].

below 30 m/min tool life becomes short in propertional to the increase of cutting speed. And above 30 m/min a sudden decrease of tool life appears. But the total value of tool life is much more prolonged when cooled cutting than that of normal cutting. And the trend is remarkable on the range of high cutting speed. The reasons are that in case of using Co as bond material of sintered diamond tool, the heat expansion rate of diamond tool is 1.2×10^{-6}, which is different from the value of Co, 14.0×10^{-6} and therefore the bridge parts between the particles of diamond are affected by large thermal stresses.

Fig. 7 shows the observation of thermal tensile stress in structure of tool influenced by cutting temperature. If grain boundary temperature considering grain boundary layer of a diamond grain width from outer surface is uniform, it is as follows:

Here, if the displacement by thermal expansion of C_o and diamond bridge are designated by X_{co}, X_d respectively and C_o caused by the rise in temperature compresses the constraint of axis of diamond, thermal expansion C_o expands diamond bridge by Xd'. And these relations of displacements are as follows[13]:

$$X_{co}-X_{co}'=Xd+Xd' \qquad (1)$$

If C_o, thermal expansion of diamond, the thickness of grain boundary layer and the rise in temperature of all grain boundaries are designated by α_{co}, α_d, D and ΔT respectively, the amount of free thermal expansion of each state is as following equation.

$$X_{co}'=\alpha_{co}\times\Delta T\times D,\ Xd=\alpha_d\times\Delta T\times d \qquad (2)$$

And if Young's modulus of diamond and C_o are designated by E_{co} and if thermal tensile stresses of them are denoted by σ_{co} and σ_d respectively, the following equation is given by

$$X_{co}'=D\times\sigma_{co}/E_{co},Xd'=D\times\sigma_d/Ed \qquad (3)$$

If the cross section of diamond and C_o are designated by A_{co} and A_d respectively, the occupied area of C_o per one bridge is 1/n in case of the number of bridge, n and the balance of force is as followed:

$$\sigma_{co}\times A_{co}\times1/n=\sigma_d\times A_d \qquad (4)$$

In equation (1), (4) thermal shear stress (GPa) acting on bridge is as follows:

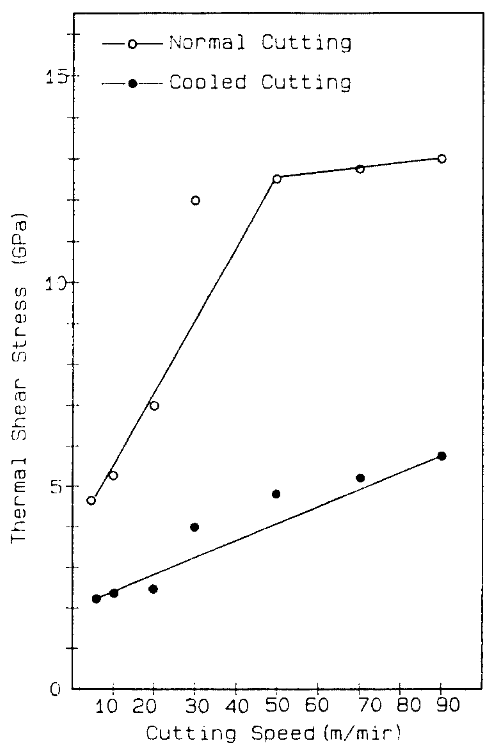
$$GPa=\frac{E_{co}\times A_{co}\times E_d\times(\alpha_{co}-\alpha_d)\times\Delta T}{E_{co}+A_{co}+n\times A_d\times Ed} \qquad (5)$$

In eq. (5) the value of thermal shear stress is determined by diamond grain, bridge, C_o, the ratio of ingredients of void section, constant of material and the rise in temperature, etc. Fig. 8 shows the determined thermal shear stress on the basis of actually measured cutting temperature Fig. 8 during cutting process. Tensile stress in bridge, caused by thermal expansion of C_0 is determined by normal temperature during cutting, cooling condition and cutting speed and decreases in proportion to the capacity rate in grain boundary of bridge. In this result, sudden change of temperature occurs due to cooling condition and cutting speed and the process of normal cutting takes above thermal crack stress 3.8 GPa according to its being formed in the range of 4.8-13.0 GPa and bridge cracks. Therefore because stress concentration caused by critical formation taken by external force takes place during cutting process of ceramics with diamond, it is estimated that thermal expansion together with the rise in cutting temperature is influenced by tool's damage.

4. 2 Relation between cooling of tool and friction surface

Fig. 9 represents a mode of cutting force of ceramics which shows that there is the greatest thrust force, which is contrast to cutting force which is greatest in metal cutting.

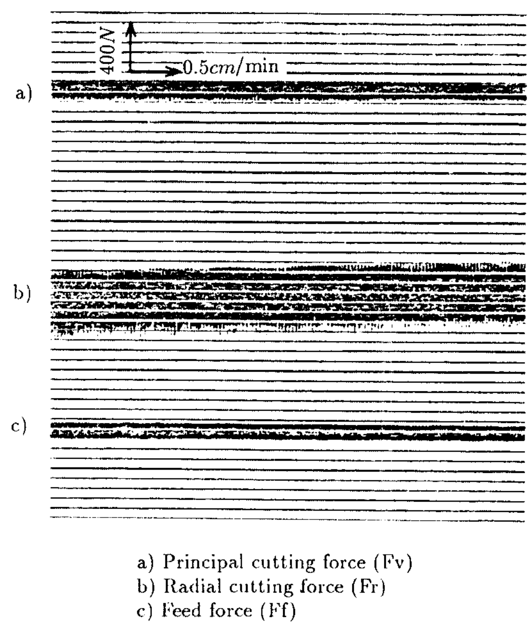
Fig. 10 shows the friction coefficient during cutting of sintered diamond tool and alumina ceramics, which is obtained by detecting the magnitude of thrust force and cutting force after cutting time 10 sec. Here increasing cutting speed makes thrust force and friction coefficient small and principal stress and shear stress of tool caused by friction contact become small. But diamond tool is expected to be damaged by thermal stress as 4.1 explained. Therefore because normal cutting, on its starting, induces the increase of cutting force together with tool's small crack, its friction coefficient is larger than that of



Feed : 0.1 mm/rev, Depth of Cut : 0.3 mm/rev

Tool : Sintered Diamond(0,0,5,5,15,15,0.8)

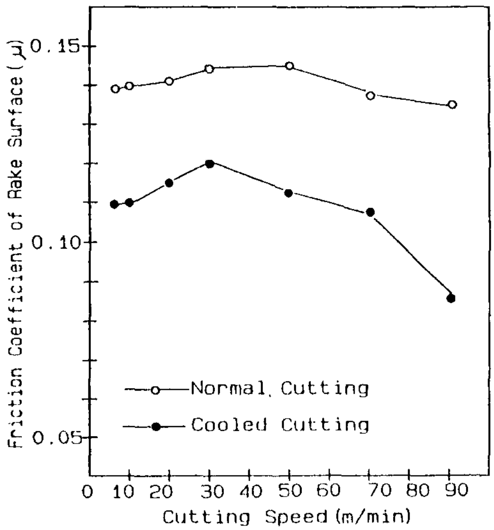
Fig. 8. Thermal tensile stress at variable cutting speed.



Cutting Speed : 30 m/min Feed : 0.1 mm/rev

Depth of Cut : 0.3 mm/rev Tool : Sintered Diamond

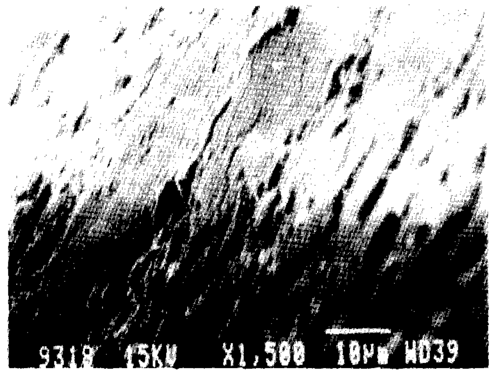
Fig. 9. Cutting force patterns of ceramics in cooled cutting.



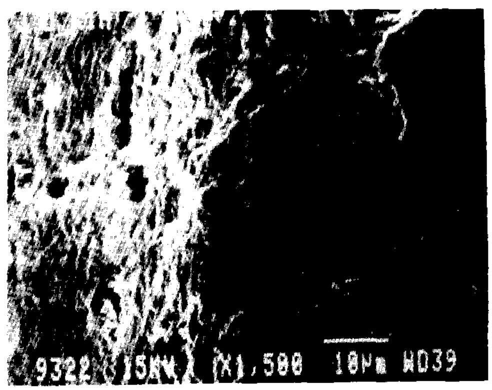
Feed : 0.1 mm/rev   Depth of Cut : 0.3 mm/rev

Tool : Sintered Diamond(0,0,5,5,15,0.8)

Fig. 10. Relation of cutting speed and friction coefficient between sintered diamond and alumina ceramic.



a) Normal cutting, cutting time : 1min



b) Cooled cutting, cutting time : 5min

Cutting Speed : 30m/min   Depth of Cut : 0.3 mm/rev

Feed : 0.1 mm/rev   Tool : Sintered Diamond

Fig. 11. Patterns of contact rake surface of sintered diamond specimen in normal and cooled cutting.

cooled cutting. And as for cutting, because it is imposed on continuous effect of friction and stress, it can be considered to have fatigue fracture like sintered diamond. Here considering the characteristics of ceramics cutting tool, when the limit of potential energy exceeds that of cereamics around low speed it goes through from step (1) to (2) (3) being the form of cutting chip as shown Fig. 4. But at high speed, due to going through from step (1) to (4), the friction coefficient greatly decrease together with decline of cutting resistance.

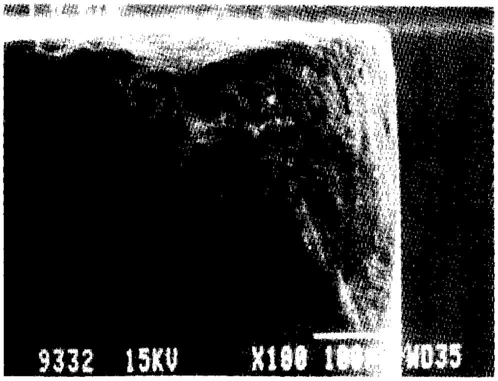
Fig. 11 represents cutting edge nose of tool showed during normal and cooled cutting in condition of the cutting speed 30 m/min of the sintered diamond tool. Cutting edge nose cutted on normal temperature (a) shows the grain boundary failure of diamond in the contact point and the free of the particle. This heat of minute structure of tool is spread in the whole contact areas in proportion to the increase of friction speed, of which rate is displayed severely.

Besides, in the friction surface machined by cooled cutting, it can be seen very little amount of heat of surface glowing along the friction direction even though it takes 5 min for friction time to cut in contrast to 1 min, normal cutting time. This is because the coefficient of friction diminishes and the max. Principal stress of stress range diminishes in friction contact and the heat of minute structure is lessoned by the cooling effect.

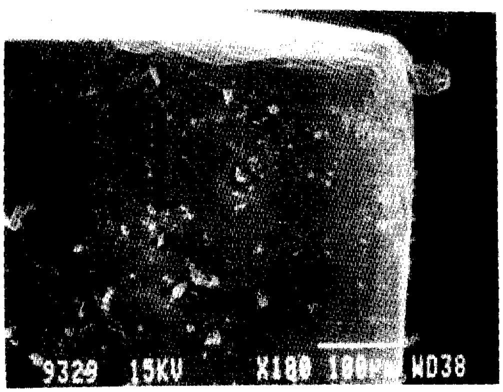
The heat of structure caused by maximum shear stress observed by the photograph of microscope indicates remarkable change of structure.

So it is concluded that the main effect to tool wear is affected more by the cutting temperature of tool than by max. shear stress.

Fig. 12 is a photograph of SEM which shows flank wear surface on tool face in normal and cooled cutting. On normal cutting, in case of cutting speed 30 m/min wear surface spreads during one-minute cutting and also tool life shortens. It's effect is indicated by the surface roughness of machined surface and is well shown in Fig. 13. Fig. 14 shows the case



a) Normal cutting, cutting time : 1min



b) Cooled cutting, cutting time : 5min

Material Cut : Alumina Ceramic

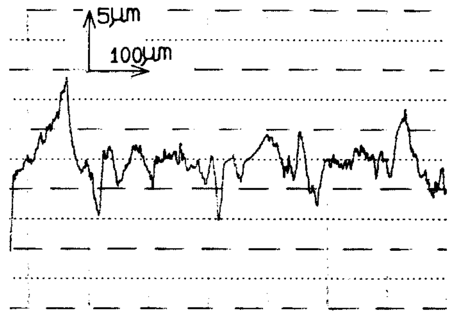
Tool : Sintered Diamond

Tool Geometry : 0,0,5,5,15,15,0.8

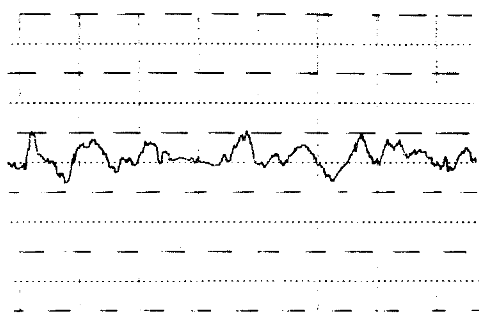
Depth of Cut : 0.3 mm/rev Feed : 0.1 mm/rev

Cutting Speed : 30m/min

Fig. 12. Typical flank wear patterns of sintered diamond tool.



a) Normal cutting

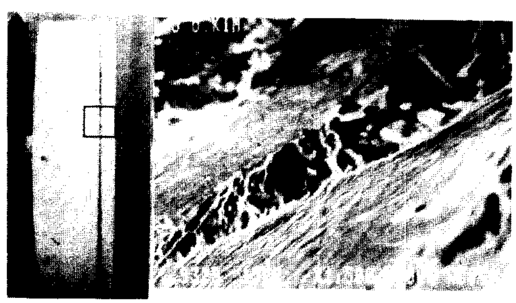


b) Cooled cutting

Cutting Speed : 30m/min Feed : 0.1 mm/rev

Depth of Cut : 0.3 mm/rev

Fig. 13. Results of surface roughness.



Cutting Speed : 30m/min Depth of Cut : 0.3 mm/rev

Feed : 0.1 mm/rev Cutting time : 4 min

Tool : Sintered Diamond Tool(0,0,5,5,15,15,0.8)

Fig. 14. Typical patterns of graphitization of ceramics in machining.

of machining in condition of normal cutting, cutting speed 30 m/min. If it takes above 4 minutes for diamond tool to cut, it transforms into graphite and loses the original mechanical properties. That transform temperature is lower in the air than in a vacuum and its phenomenon is easily seen are because diamond tool transforms into graphite according to the following chemical reaction such as $C+O \rightarrow CO$, $C+2O \rightarrow CO_2$ around O_2[14]. Therefore it is considered that tool has a pattern of tool crack from the point of its being carbonized and, together with development of tool wear, cutting heat has much to do with tool damage of free. Especially, even though cutting chips of ceramics are uniform due to being formed by malleability crack[15], some items are resulted as follows: If cutting temperature is lowered to ultimate low temperature, which causes that thermal stress is compressed and also stress distribution of tool face spreads, it helps tool crack to be compressed.

5. Conclusions

In order that ceramics can be machined by sintered diamond tool, the following results are obtained in the experiment of ultimate low temperature cooling air composed by liquefied Nitrogen

1) Under the cutting speed of 30 m/min the cutting temperature shown on the cutting tool face reaches 480°C in normal temperature, 95°C in the cooled cutting. So it is expected that the remarkable cooling effect of the liquid nitrogen is obtained.

2) The damage of diamond tools treated with ceramics is due to the thermal expansion according to the increase of cutting temperature.

3) The tool wear is due to the following phenomena, that is to say, the decrease of the friction coefficient in the cooled cutting and of the max. Principal stress in the stress range and finally the reduction of the heat of the small tissues by the cooling effect.

4) The following phenomena in this experiment are shown. The diamond tool is oxidized carbonized according to the increase of the cutting temperature when we cut them under the normal temperature.

5) If the ceramics are cutted under the ultimate low temperature the crack of the face treated with ceramics is developed and the pitch of the lost parts and the stress range affected on the tool face extend. So it is supposed that cutting ceramics under the ultimate low temperature has effect on control of the tool's destruction.

6) The thrust force in the ceramics treatment is shown on a remarkably large scale in comparison with the cutting force and the feed force. The thrust force increases as the cutting time lasts but the cutting force reduces owing to the cooled cutting. This phenomenon has much to do with the tool's damage of free and it is shown that cooled tools in the ultimate low temperature makes the damage of free reduce.

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