# A Study on Critical Depth of Cuts in Micro Grooving

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Ultra precision diamond cutting is a very efficient manufacturing method for optical parts such as HOE, Fresnel lenses, diffraction lenses, and others. During micro cutting, the rake angle is likely to become negative because the tool edge radius is considerably large compared to the sub-micrometer-order depth of cut. Depending on the ratio of the tool edge radius to the depth of cut, different micro-cutting mechanism modes appear. Therefore, the tool edge sharpness is the most important factor which affects the qualities of machined parts. That is why diamond, especially monocrystal diamond which has the sharpest edge among all other materials, is widely used in micro-cutting. The majar issue is regarding the minimum (critical) depth of cut needed to obtain continuous chips during the cutting process. In this paper, the micro machinability near the critical depth of cut is investigated in micro grooving with a diamond tool. The experimental results show the characteristics of micro-cutting in terms of cutting force ratio (Fx/Fy), chip shape, surface roughness, and surface hardening near the critical depth of cut.

**Key Words :** Micro Grooving, Diamond Tool, Critical Depth of Cut

## Nomenclature

NRA : Negative rake angle
t : Depth of cut
tc : Critical depth of cut
Fx : Principal force
Fz : Thrust force
N : Normal force
$\mu$ : Friction coefficient
r : Tool edge radius
Pc : Critical point

## 1. Introduction

As the IT (Information Technology) era progresses, light-based systems for communication and display are greatly required. This is the reason why various optical parts should be manufactured to deal with light in accordance with a variety of applications. Inherently, optical parts such as HOE (Holographic Optical Element), Fresnel lenses, lenticular lenses, and diffraction lenses should satisfy strict requirements of ultra high form accuracy and surface quality. Furthermore, the optical parts should be as compact as possible for the convenience of practical use.

Although many manufacturing methods for optical parts have been developed, ultra-precision diamond cutting with micrometer-order depth of cut is considered to be the most efficient because it is able to produce a three-dimensional shape as well as a mirror-like surface due to the sharp edge of the diamand fool.

In micro cutting, as opposed to macro cutting,

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the rake angle is likely to become negative because the round edge of a sharp tool occupies most of the contact line between the tool and the workpiece. This might sometimes cause plowing and a poor surface, or sometimes burnishing and a shining surface, depending on the depth of cut. A critical depth of cut is defined as the depth of cut where the micro cutting performance rapidly changes. Usually, the critical depth of cut has been determined as the depth where the characteristics of burr, surface roughness, chip formation, etc. drastically changes (Leung, 1998 ; Ahn, 2000 ; Kumbera, 2001).

Lucca et. al reported that the effects of plowing due to a large "effective" negative rake angle that results from the tool edge radius has become important in micro-machining. Moriwaki and Okuda and Furukawa and Moronuki have observed that the increase in specific energy dominates the force system in the diamond turning process with a sub-micrometer depth of cut.

As the depth of cut becomes the same order as the tool edge radius, the energy consumption of plowing which is not directly responsible for material removal, is extremely important in its effect on the tool performance, workpiece surface intergrity, and subsurface damage, and in determining the minimum machinable depth of cut. (Lucca, 1991 ; Moriwaki, 1989 ; Moronuki, 1988) Many studies have been reported on the mechanism of micro-chip formation, specific cutting force, and minimum thickness based on the relationship between the tool sharpness and the depth of cut. (Leung, 1998 ; Yuan, 1996 ; Yang, 1992) However, there are few studies on the minimum depth of cut considering the friction effect between the tool edge and the workpiece.

In this study, defining the critical depth of cut as the thinnest cutting depth where a flow-type chip is made, a model is proposed for determining the critical depth based on the Shaw's cutting force model with an emphasis on the friction between the tool and the workpiece. This is experimentally investigated through the change in the micro-machinability near the critical depth of cut.

## 2. Modeling of Critical Depth of Cut and Simulation

### 2.1 Theoretical relationship between critical depth of cut and tool edge radius

Figure 1 shows the micro-cutting mechanism with a negative rake angle (NRA) when the depth of cut is less than the tool edge radius ($r$). Undergoing severe plastic compression and then elastic recovery, the un-cut material under the round tool edge becomes the machined surface. The elastic recovery, $t_s$, which depends on the Young's modulus of the workpiece, causes a strong repellant force on the tool's clearance face. It makes the thrust force ($F_z$) more dominant than the principal force ($F_x$), especially at a sub-micrometer depth of cut. This likely results in a violent fluctuation of the cutting force, or an unstable cutting process. According to the preliminary micro-machining experiments for the study, $F_x/F_z$ was found to be in the range from 0.7 to 1.3 and some cutting characteristics were found to reverse around $F_x/F_z=1$.

For a smaller depth of cut than the critical depth, that is $F_x/F_z<1$, the deformation by the thrust force would be dominant while the chip formation by the principal force would be negligible because the thrust force would become larger than the principal force. Then, the tool is likely to plow and burnish the un-cut material along the clearance face. In the range over the critical depth, the chip formation by the principal force would be more dominant than the deformation by the thrust force. This might make the cutting process more stable where flow-type chips are produced. In this study, based on the experimental findings and the qualitative analysis, $F_x/F_z=1$ is assumed as a criterion for determining the critical depth of cut.

The normal force ($N$) and the tangential force ($\mu N$) are derived as follows :

$$\begin{aligned} N &= F_z \cos\theta + F_x \sin\theta \\ \mu N &= F_x \cos\theta - F_z \sin\theta \end{aligned} \tag{1}$$

where $F_x$ is the principal force, $F_z$ is the thrust

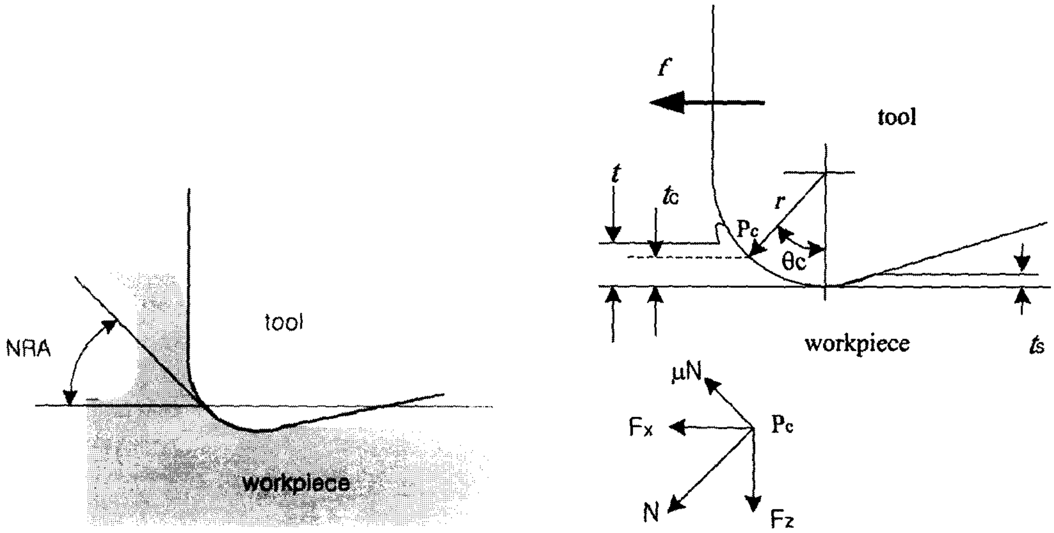



**Fig. 1** Schematic diagram of micro cutting mechanism

force, $\mu$ is the friction coefficient between the cutting tool and the workpiece.

From Eq. (1), the angle $\theta$ can be calculated as shown in Eq. (2).

$$\theta = \tan^{-1}\left(\frac{F_x - \mu F_z}{\mu F_x + F_z}\right) \tag{2}$$

Assuming $F_x/F_z = 1$ at the critical depth of cut, the critical angle ($\theta_c$) is derived as a function of $\mu$.

$$\theta_c = \tan^{-1}\left(\frac{1-\mu}{\mu+1}\right) \tag{4}$$

Then the critical depth of cut is geometrically expressed as follows.

$$t_c = r(1-\cos\theta_c) = r\left(1 - \frac{1+\mu}{\sqrt{2(1+\mu^2)}}\right) \tag{4}$$

Therefore, Eq. (4) shows that the critical depth of cut for a combination of diamond tool and workpiece can be calculated if the tool edge radius and the friction coefficient are given.

### 2.2 Simulation results

It is certain from Eq. (4) that the critical depth of cut relates closely to the friction coefficient and the tool edge radius. In general, the friction coefficients between diamond and metals are known to be in the range from 0.05 to 0.2, depending on the test environment. (De Barros a 2001 ; Schumitt, 1999 ; Field, 1996) Therefore, from Equation (4), the critical depth of cut for those friction coefficients would vary from 0.17 to 0.26 $\mu$m as indicated by the thick solid line in Fig. 2. The larger the friction coefficient, the thinner the critical depth of cut.

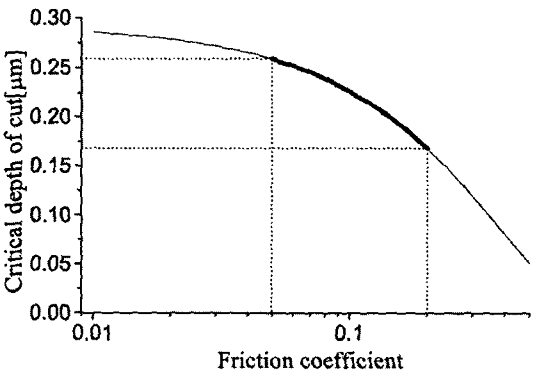
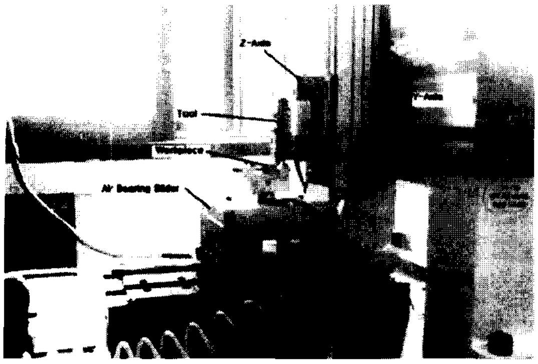



**Fig. 2** Simulated critical depth of cut versus friction coefficients

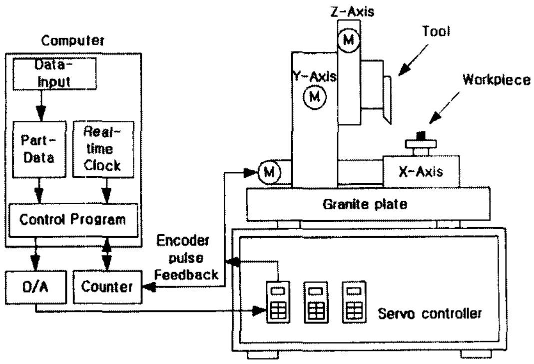
## 3. Experimental Equipment and Conditions

### 3.1 Experimental equipment

Figure 3 shows a photograph and a schematic diagram of the machine tool used in this study. The machine tool is composed of three translational axes, $X$, $Y$, and $Z$. The $X$-axis is guided



(a) Photograph of the micro machine tool




(b) Schematic diagram of the micro machining system

**Fig. 3** Experimental Equipment

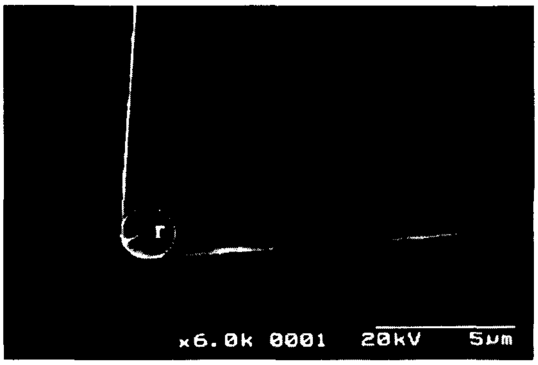



**Fig. 4** SEM photograph of the diamond tool edge

by an air bearing with no friction and driven by a steel belt whereas the $Y$ and $Z$ axes are actuated by ballscrews. The resolution of the $Z$ axis having a ball reducer is 0.02 $\mu$m. The machine tool has a semi-closed loop control system that controls the position as well as the feedrate with encoder signals.

### 3.2 Experimental conditions

Square-type mono crystal diamond tools with a rake angle of 0°, a clearance angle of 8°, and a width of 1 mm were used in the experiments. Using 7-3 brass and Al 7075 as workpieces, micromachinability was investigated for square grooving under various depth of cuts from 0.1 to 0.5 $\mu$m and a feedrate of 3 mm/sec. Figure 4 shows a SEM photograph of the tool edge with a radius of 1 $\mu$m.

## 4. Experimental Results

### 4.1 Friction coefficient

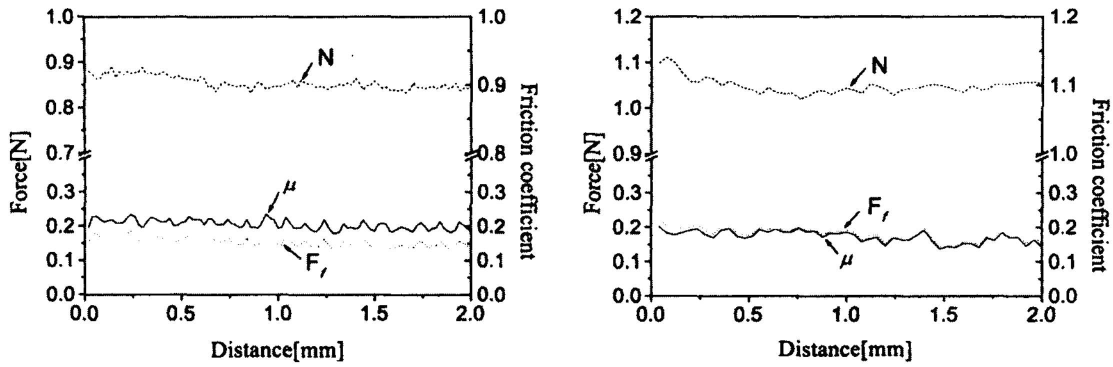
A friction test was conducted to measure the friction coefficients, which is calculated as the ratio of the friction force ($F_f$) and the normal force ($N$), $\mu = F_f/N$, between the workpiece and the diamond tool. Figure 5 shows the results of the friction test. The friction coefficient of 7-3 Brass is about 0.2 and for Al7075 it is about 0.17. From Fig. 5, the critical depth of cut is theoretically expected to be about 0.17~0.18 $\mu$m.

### 4.2 Cutting force

Figure 6(a) and 6(b) show variations of the principal force and the thrust force for 7-3 Brass and Al 7075, respectively. The thrust force is larger than the principal force at 0.1 $\mu$m depth of cut, but the principal force increases more steeply than the thrust force as the depth of cut increases. This is a good experimental evidence of the critical depth of cut existing where the magnitudes of $F_x$ and $F_z$ are reversed.

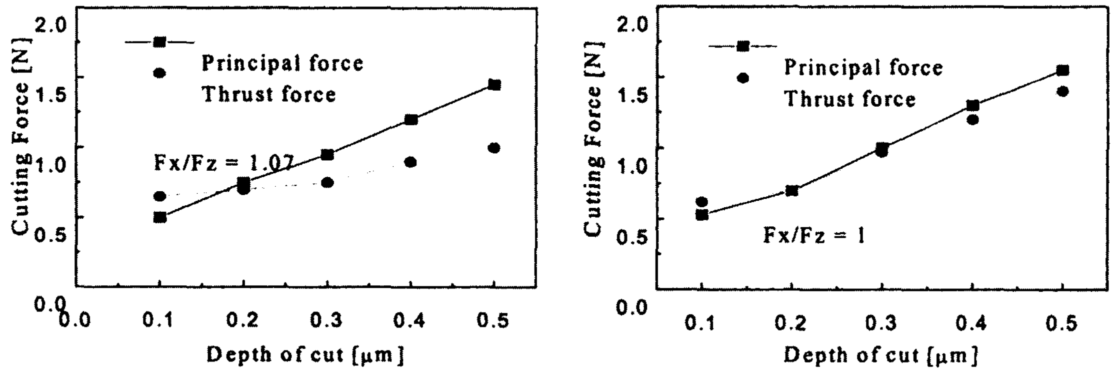
The switching occurs at a depth of cut around 0.18 $\mu$m and 0.2 $\mu$m for 7-3 Brass and Al 7075, respectively.

However, the simulated values are smaller by about 0.02 $\mu$m than the experimental ones. The reason may be that the variation of the contact surface of the tool and the workpeace caused by




(a) For 7-3 Brass
(b) For Al 7075

**Fig. 5** Friction forces and coefficients between workpieces and diamond tools

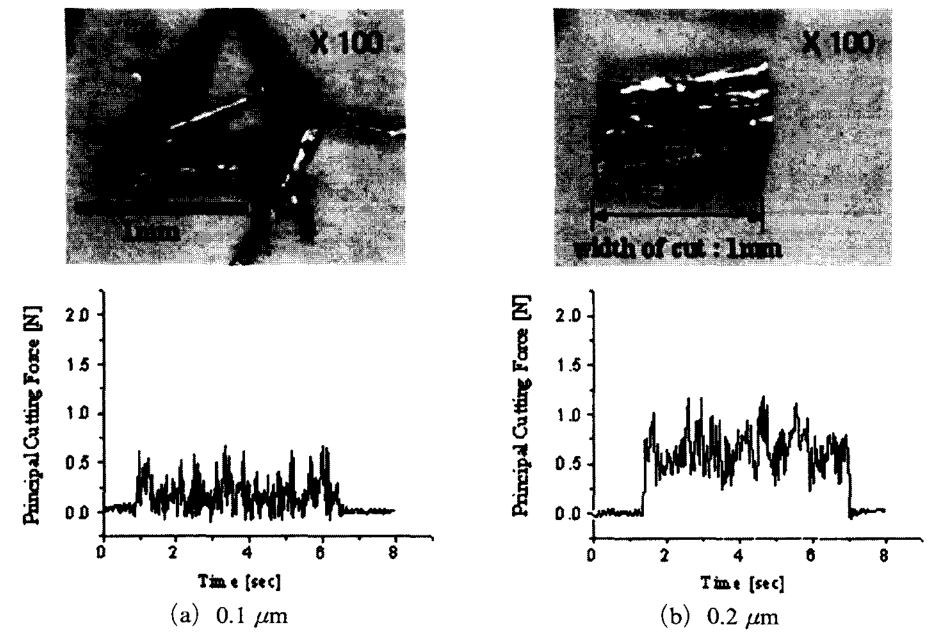



(a)
(b)

**Fig. 6** Averaged cutting forces versus depth of cut

Chip

Principal force




(a) 0.1 μm
(b) 0.2 μm

**Fig. 7** Comparison of chip shapes

vibrations in the real cutting process would make the friction coefficient smaller.

Figure 7 shows variations of the principal forces and the chip shapes at 0.1 $\mu$m and 0.2 $\mu$m depth of cut. At 0.1 $\mu$m, the principal force fluctuates from 0 to 0.5 N. This results in some parts of the workpiece being left uncut intermittently, which results in the non-uniform chips as shown in Fig. 7. On the other hand, at 0.2 $\mu$m depth of cut, the force level goes up to about 0.5 N and the chip changes into a flow-type. This is an additional evidence that the cutting process is unstable below the critical depth of cut.

### 4.3 Quality of machined surfaces

Roughness of the machined surfaces was also measured to investigate how it was affected by the critical depth of cut. Figure 8 shows the measurement results. It can be seen that the machined surface is best at about 0.16 $\mu$m, with the critical depth of cut at 0.2 $\mu$m, because it is the thinnest depth of cut to make the flow-type chip.

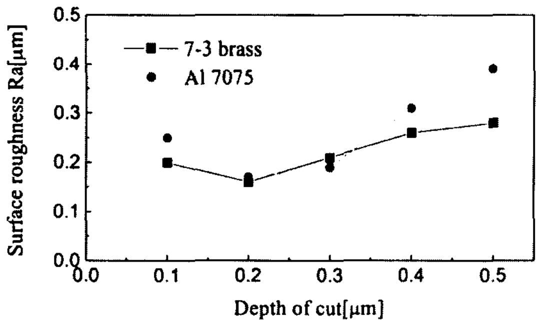



**Fig. 8** Surface roughness versus depth of cut

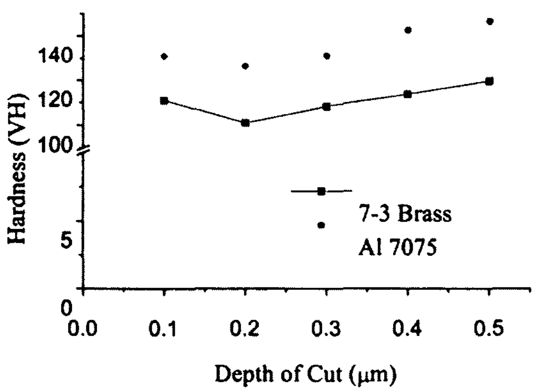



**Fig. 9** Micro-hardness versus depth of cut

Micro-hardness was measured to investigate the hardening effect of the machined surface. Figure 9 shows that the hardening effect is smallest at the critical depth of cut. It is believed that the increase of hardening at less than the critical depth of cut is caused by burnishing. This means that the residual stress left on the machined surface is smallest when being cut at the critical depth of cut. (Lucca, 1998)

## 5. Conclusion

In micro cutting with a diamond tool, the critical depth of cut, which is the minimum depth of cut where the flow-type chips can be produced stably was investigated theoretically as well as experimentally.

The conclusions are as follows :

(1) The critical depth of cut was decided by the tool edge radius and the friction coefficient between the workpiece material and the diamond tool.

(2) At less than the critical depth of cut, the thrust force is larger than the principal force. Thus, the cutting process is unstable and the machined surface becomes poor.

(3) When cutting at the critical depth of cut, a flow-type chip is generated and surface roughness becomes the best and surface hardening the least.

To lower the critical depth of cut, a smaller tool edge radius or a higher friction coefficient is required. Therefore, it is believed that not only sharpening the tool edge but also increasing the friction coefficient physically/chemically is very effective to get a high quality micro-machined surface.

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