EFFECT OF POLAR ORGANIC SUBSTANCE ON BURR FORMATION IN ORTHOGONAL CUTTING

Gyun-Eui Yang* and In-Chang Cha**

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The initiation of burr formation is characterized by the initial negative shear angle and the initial tool distance which are obtained from the minimum energy principle and energy conservation at the chip/burr transition point. Specially in this report the rollover burr is dealt as a specific case of the chip formation process in the final stage of cut, which the tool moves toward the end of workpiece. The purpose of this paper is to experimentally invesigate the burr formation mechanism near the end of cut by using a copper with various cutting conditions and tool geometries, and the influence of the surface active medium, that was used to reduce the burr size and improve the machinability, upon the mechanism of burr formation in the orthogonal cutting using the milling machine.

Key Words: Polar Organic Substance, Burr Formation, Negative Shear Angle, Burr Size, Orthogonal Cutting

NOMENCLATURE

- A_c : Cross sectional area of the uncut chip
- b : Width of chip
- d_s : Movement of negative shear plane as the tool moves by "dx"
- F_s : Shear force in the negative shear plane
- K_o : Yield shear strength depending on the cutting condition
- l : Length of the initial negative shear plane
- l' : Length of deformed negative shear plane
- M : Bending moment
- t : Depth of cut
- t_c : Chip thickness
- W : Distance between the tool and the end surface of workpiece
- W_{b1} : Work done for plastic shear deformation
- W_{b2} : Work done for plastic bending deformation
- ΔW_{chip} : Work done for the chip formation
- ΔW_{burr} : Work done for the burr formation.
- α : Rake angle
- γ : Shear strain
- σ_e : Yield strength of the workpiece
- τ_s : Shear stress on the shear plane
- ϕ_n : Initial negative shear angle
- ϕ_n' : Negative shear angle
- $d\phi_n$: Small deformed quantity of ϕ_n

1. INTRODUCTION

Burr has been defined as the undesirable projection of materials as a result of plastic flow from a cutting or shearing operation. Burr formation is unavoidable in all kinds of machining operation. In most cases, burr must be removed to allow the proper fitting of assembled parts and to insure safe mand proper functioning. There are several techniques to minimize the cost for deburring (Gillespie, L. K.,1981). The burr size relies on the burr formation. Knowledge on the mechanism of the burr formation in metal cutting helps prevention of the burr formation or minimization of the size of burr on machined parts. Gillespie defined four kinds of burrs, such as Poisson burr, rollover burr, tear burr, and cut-off burr depending on the mechanism (Gillespie, L.K., 1976).

Especially in this report the rollover burr will be dealt as a specific case of the chip formation in the final stage of cutting. The rollover burr is formed by formation of material over the edge when the tool exits the workpiece. The mechanism of the chip formation changes near the end of cut.

The existence of a negative shear plane has been previously inctroduced as an important feature for tool fracture studies on tool exit (Pekelharing,A.J., 1978). Localized shear deformation along the fracture plane was observed. The result of the fracture along the negative shear plane during burr formation was referred as foot formation. Foot formation will be considered here as a kind of burr formation for certain materials. Gillespie (1977) has also proposed a simple model for rollover burr formation considering the deformation at the end of cut as bending deformation.

Dornfeld,etc, (1988) proposed burr formation model when no fracture occurrs during burr formation assuming the deformation consists of shearing and bending deformation. This assumption is based on the observation of burr formation during clay machining test. Orthogonal machining tests inside SEM (Scanning Electron Microscope) was done to verify the model.

As a approaching method to minimize burr size during burr formation in practically, this paper describes the influence of magic ink (oil ink) coated on the free surface of workpiece as a polar organic substance on the mechanism of burr formation near the end of cut in the orthogonal cutting of copper to

*Department of Mechanical Engineering, Chonbuk National University, Chonju 560-756, Korea
**Department of Industrical Electronic, Kolon Engineering, Seoul 100-170, Korea

observe the reduction of burr size and the improvement of machinability through the theoritical and experimental investigation of Rehbinder effect. Rehbinder(1947) attributed the reduction in the work of cutting achieved by the use of surface-active media, such as palmitic acid or cetyl alcohol to the softening action of surface-active agents during plastic deformation. This softening action is known as the Rehbinder effect.

The improvement of machinability and burr size reduction are dissussed by coating the work with polar organic materials upon the mechanism of burr formation at the end of cut.

2. THEORETICAL CONSIDERATION

The chip formation mechanism at the steady-state process is done by shearing the workpiece to form the chip on its free surface, resulting in positive shearing. As the tool approaches near the end of workpiece, there is a transition point that the chip formation stops and the negative shearing occurs, and a negative shear angle is formed. Considering the small advance of tool by "dx" at the instance of transition from the chip formation to the negative shearing, it can be assumed that the work done for the chip formation is equal to the work done for the negative shearing by the energy conservation and the continuity of cutting force.

$$\Delta W_{chip} = \Delta W_{burr} \tag{1}$$

2.1 Chip Formation Mechanism

It is assumed that the continuous-chip formation is employed in this experiment, and the simple shear plane model suggested by Merchant(1945) can be applied. From Fig. 1 to determine the shear angle ϕ, cutting ratio r_c is given by

$$r_c = \frac{t}{t_c} = \frac{\sin\phi}{\cos(\phi-\alpha)} \tag{2}$$

and after rearrange Eq. (2), the shear angle is given by

$$\phi = \tan^{-1}\frac{r_c\cdot\cos\alpha}{1-r_c\cdot\sin\alpha} \tag{3}$$

As shown in Fig. 1 the shearing force F_s and normal force F_{ns} on the shear plane is written as,

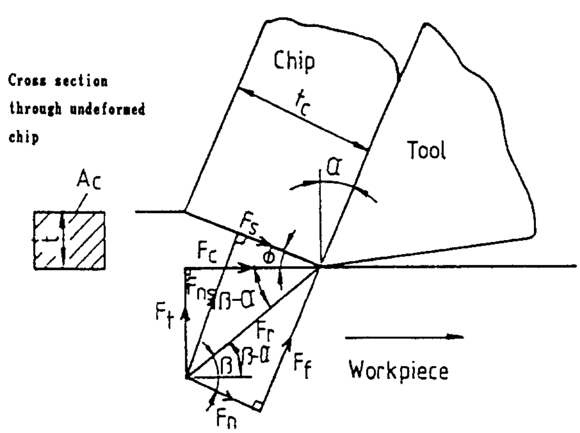


Fig. 1 Force diagram for orthogonal cutting

$$F_s = F_c\cdot\cos\phi - F_t\cdot\sin\phi \tag{4}$$
$$F_{ns} = F_c\cdot\sin\phi + F_t\cdot\cos\phi \tag{5}$$

The area of shear A_s is given by

$$A_s = A_c/\sin\phi \tag{6}$$

and thus the shear stress τ_s and normal stress σ_s on the shear plane can be written as,

$$\tau_s = \frac{F_s}{A_s} = \frac{(F_c\cdot\cos\phi - F_t\cdot\sin\phi)\cdot\sin\phi}{A_c} \tag{7}$$
$$\sigma_s = \frac{F_{ns}}{A_s} = \frac{(F_c\cdot\sin\phi - F_t\cdot\cos\phi)\cdot\sin\phi}{A_c} \tag{8}$$

and also the normal force F_n and the friction force F_f on the rake face of the tool is given by

$$F_n = F_c\cdot\cos\alpha - F_t\cdot\sin\alpha \tag{9}$$
$$F_f = F_c\cdot\sin\alpha - F_t\cdot\cos\alpha \tag{10}$$

The shear stain in shear zone is

$$\gamma = \cos\alpha/[\sin\phi\cdot\cos(\phi-\alpha)] \tag{11}$$

It is assumed that the unit length of workpiece is cut, and then the shear energy E_s on the shear plane is

$$E_s = \tau_s\cdot\gamma\cdot b\cdot t \tag{12}$$

also the friction energy E_f on the rake face of the tool is

$$E_f = F_f\cdot r_c \tag{13}$$

Thus the work done by the small distance "dx" for chip formation is obtained by Eqs. (12) and (13)

$$W_{chip} = (E_s + E_f)\cdot dx \tag{14}$$

2.2 Burr Formation Mechanism

Figure.2 shows the geometrical model of burr formation mechanism. As the tool gradually approaches near the end surface of workpiece, the chip fǫrmation gradually stops and the burr is formed by negative shearing with downward direction of the workpiece. Using the model in Fig 2, it can be assumed that the deformation is composed of the plastic shear deformation and the plastic bending deformation. The

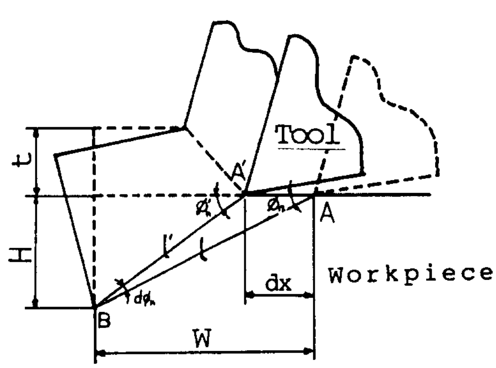


Fig. 2 Burr formation model

burr formation continues under the plastic shear and bending deformation until the tool exits the workpiece completely. Then work done for the burr formation is

$$\Delta W_{burr} = \Delta W_{b1} + \Delta W_{b2} \quad (15)$$

Assuming unit width of cut

$$\Delta W_{b1} = F_s \cdot d_s = K_o \cdot l \cdot (l - l') \quad (16)$$

So,

$$\Delta W_{b2} = M \cdot d\phi_n = 1/2 \cdot \sigma_e \cdot l'^2 \cdot (\phi_n' - \phi_n) \quad (17)$$

Eq. (15) by Eq. (16) and (17) becomes

$$\Delta W_{burr} = K_o \cdot l \cdot (l - l') + 1/2 \cdot \sigma_e \cdot l'2 \cdot (\phi_n' - \phi_n) = [K_e + 1/2 \cdot \sigma_e \cdot \tan \phi_n] \cdot W \cdot dx \quad (18)$$

From Fig. 2

$$l = W/\cos \phi_n$$
$$l' = (W - dx)/\cos \phi_n'$$
$$l \cdot \sin \phi_n = l' \cdot \sin \phi_n' \quad (19)$$

At the given cutting condition with fixed W, the initial burr formation will occur along the initial negative shear plane with an angle which satisfies the minimum energy principle (Merchant, M.E., 1945, Dautzenberg, J.H., 1981, Klamecki, B. E., 1982, 1985).

$$\frac{dW_{burr}}{d\phi_n} = 0 \quad (20)$$

thus rearrange

$$2K_o \cdot l \cdot \frac{dl}{d\phi_n} - K_o \cdot \frac{dl}{d\phi_n} - K_o \cdot l \cdot \frac{dl'}{d\phi_n} + \sigma_e \cdot l' \cdot (\phi_n' - \phi_n) \cdot \frac{dl'}{d\phi_n} + \frac{1}{2} \cdot \sigma_e \cdot l'^2 \cdot \left(\frac{d\phi_n'}{d\phi_n} - 1\right) = 0 \quad (21)$$

From Fig. 2

$$d\phi_n = 1/W \cdot \sin \phi_n \cdot \cos \phi_n \cdot dx \quad (22)$$

Substituting Eq. (18) into (20) and neglecting the higher order terms of dx, the Eq. (20) can be simplified

$$\sigma_e \cdot \sin^2 \phi_n \cdot \cos \phi_n - 1/2 \cdot \sigma_e \cdot \cos \phi_n + 3K_o \cdot \sin \phi_n = 0 \quad (23)$$

Applying Maclaurin series to simplify the Eq. (23)

$$\phi_n^8 - 14\phi_n^6 + 60\phi_n^4 + 36K_o/\sigma_e \cdot \phi_n - 90\phi_n^2 - 216K_o/\sigma_e \cdot \phi_n + 36 = 0 \quad (24)$$

Thus the initial negative shear angle can be obtained by Eq. (24), and by substituting Eqs. (14) and (18) into Eq. (1), the distance between the initial negative shearing point and the end surface of workpiece becomes

$$W = \frac{E_o + E_f}{K_o + 1/2 \cdot \sigma_e \cdot \tan \phi_n} \quad (25)$$

Assuming the point B to be a plastic hinge from the Fig. 2, the burr thickness H becomes

$$H = W \cdot \tan \phi_n \quad (26)$$

3. EXPERIMENTAL METHOD

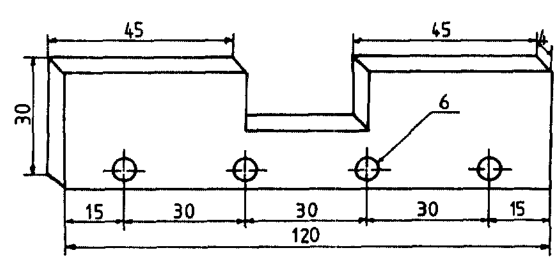
Copper is used as a workpiece in this experiment and the mechanical properties of the workpiece is listed in Table 1. Fig. 3 shows the shape of workpiece to perform the dry cutting and coated cutting with polar organic substances simultaneously. A simple straight cutting edge tool was attached on the arbor yoke of the milling machine, and a tool dynamometer platform was set up on the table. Orthogonal cutting test was then performed after fixing a small type vise on the platform of the tool dynamometer with a workpiece in the vise.

The specifications of experimental apparatus used in this experiment are shown in Table 2. Fig. 4 shows schematic diagram of experimental apparatus. The cutting speed was given as the table feed of milling machine. The cutting forces measured by the tool dynamometer were displayed in the oscilloscope during machining and recorded in the computer using charge amplifier and A/D converter. After machining each of workpieces, burr size was measured with electromicrometer by using profile projector (×50, ×100). The cutting conditions of the orthogonal cutting are listed in Table 3.

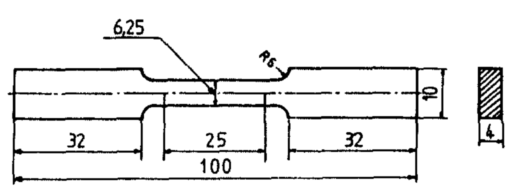
Precutting was performed sequentially at the condition of depth of cut, 0.05, 0.04, 0.03, 0.02, 0.01, 0.01, 0.01 and 0.01mm to remove the influence of previous cuts (Sakakida,1972, 1976, Yang, G.E., 1990 a,b). After observing the behavior of surface environment effect by coating the cutting fluid on the free surface of forming chip, precutting is performed so that surface effect may be removed for next cutting test. Gasoline is used as a cutting fluid for precutting. Finally the free

Table 1 Mechanical properties of the workpiece

Specimen	Yield stength (kg/mm²)	Tensile strength (kg/mm²)	Rockwell Hardness (B scale)	Condition
1	9.94	30.31	49±2(%)	dry cutting
2	6.32	21.65	40±2(%)	coated magic ink



(a) Specimen of orthogonal cutting experiment (mm)



(b) Specimen for tensile test (mm)

Fig. 3 Specimens of orthogonal cutting and tensile test surface of forming chip was cleaned with aceton, and precutting was finished at a depth of cut of 0.01mm in dry cutting. A layor after precutting was left on the workpiece and this was used in cutting test. The depth of cut was adjusted with electric micrometer of 0.2 μm resolution. The surface environment was given with magic ink available on the market.

Table 2 Specifications of experimental apparatus

1. milling machine	
universal milling machine	
feed rate	: 15~3600 mm/min
bed	: 1300×280 mm
2. tool dynamometer	
Kistler Instrument type	: 9257 A
maximum measuring range : 5000N	
resolution	: <0.01 N
3. charge amplifier	
Kistler Instrument type	: 5001
measuring range	: ±10−500,000 pc
accuracy of range	: ±1%
4. IBM PC/AT	: CPU 80286
5. A/D converter	: ADC 574 A
measuring range	: ±5 V
6. tool microscope	
model	: Nikon
magnification range	: ×30
7. profile projector	
model	: Nikon, CM-6F.6P
magnification range	: ×50, ×100

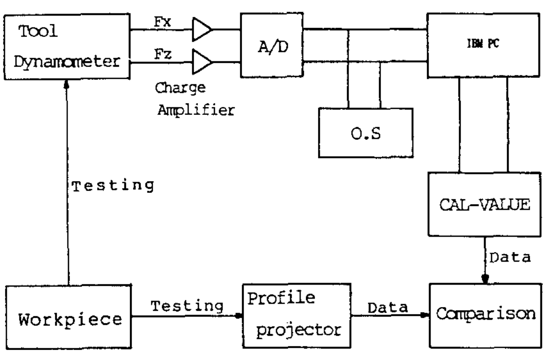


Fig. 4 Schmetic diagram of experimental apparatus

Table 3 Cutting conditions

Work material	: copper
Width	: 4 mm
Tool	: single straight cutting edge SKH9
Rake angle	: 0~30 deg
Clearance angle	: 6 deg
Radius of cutting edge	: less then 2 μm
Cutting speed	: 342 mm/min
Depth of cut	: 0.01~0.12 mm
Coating material	: Magic ink ($C_6H_5CH_3+C_4H_9OH+C_6H_4(CH_2)_2+C_6H_{12}O_2$)

4. EXPERIMENT RESULTS AND DISSCUSSIONS

Figure.5. shows the burr which is enlarge 100 times by using an optical microscope with a cutting condition: rake angle 20° depth of cut 0.05 mm. If complete shearing occurred, probably the angle between free surface and end of cut surface would be formed in 90°. But the burr, which is formed as a part of chip, remains at the exit of cut due to plastic flow of the

(a) dry cut

(b) coated cut

Fig. 5 Photomicrograph of end face burr formation. condition : depth of cut=0.05 mm, rake angle=20°

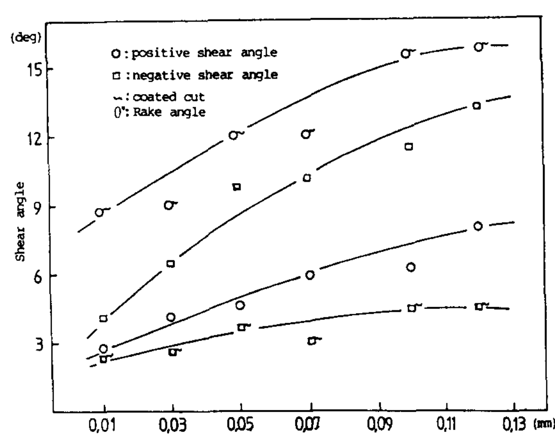


Fig. 6 The relation between shear angle and depth of cut

material. In Fig. 5(a), the burr thickness is large due to initial negative shear angle and distance between initial negative shearing point and end face. In Fig. 5(b), the burr thickness is reduced in the coated cut by the effect of surface environment.

Figures.6~9 shows the relation between shear angle and depth of cut with rake angle of 0° 10°, 20°, 30°. The shear angle is defined as the positive shear angle in chip formation and initial negative shear angle in burr formation. Here, initial negative shear angle can be obtained by Eq. (24) which above mentioned. With varying rake angle of 0°, 10°, 20°, 30°. the shear angle increases with the increase of depth of cut in chip formation, and the magnitude of shear angle is higher in coated cut than in dry cut. It is attributed to the Rehbinder effect, which has been known as a phenomenon that the mechenical strength reduces when the metal is exposed in a polar organic environment or the surface of the metal is coated with some polar organic substances, resulting in

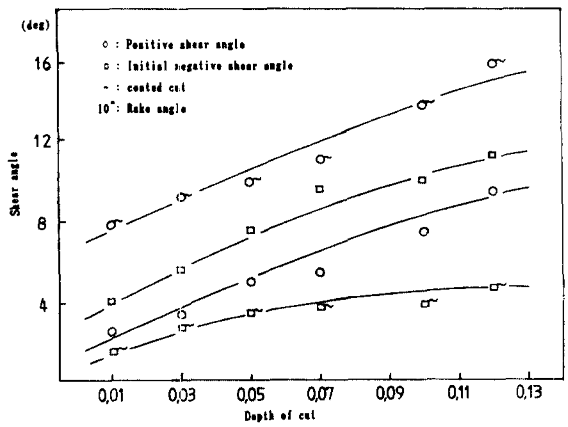


Fig. 7 The relation between shear angle and depth of cut

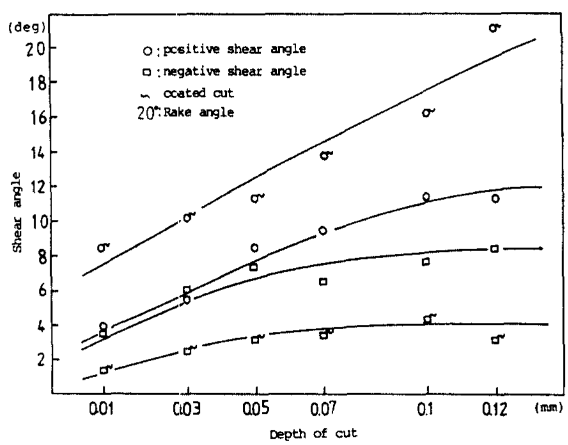


Fig. 8 The relation between shear angle and depth of cut

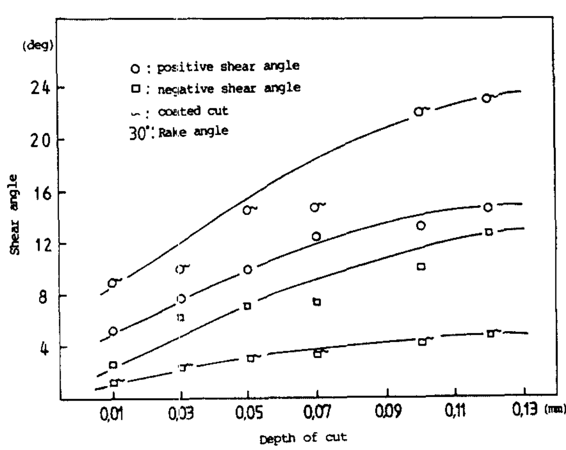


Fig. 9 The relation between shear angle and depth of cut

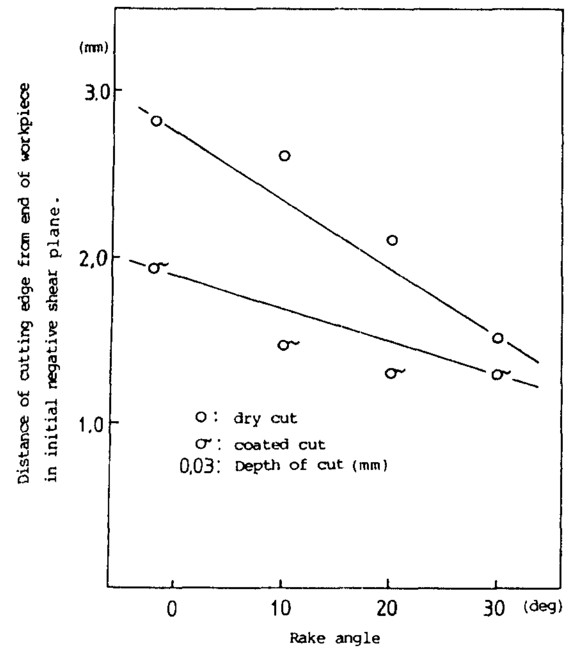


Fig. 10 The relation between distance of cutting edge from end of workpiece in intial negative shear plane and rake angle

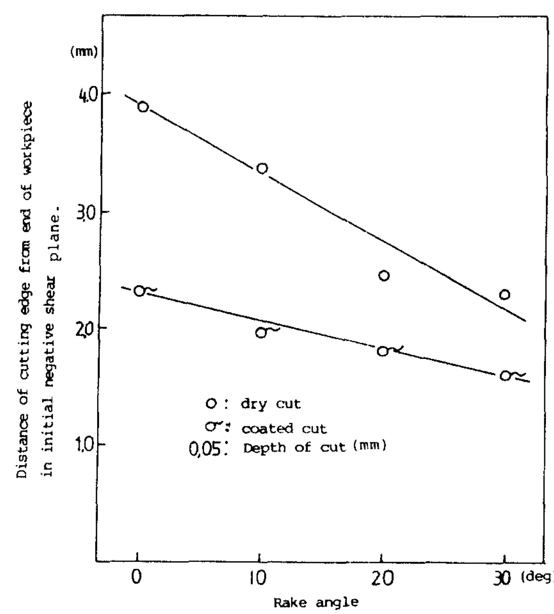


Fig. 11 The relation between distance of cutting edge from end of workpiece in intial regative shear plane and rake angle

improvement of machinability.

Initial negative shear angle increases with the increase of depth of cut. The magnitude of initial negative shear angle was larger than that of positive shear angle in the case of rake angle 0° but more increase in rake angle caused the decrease in the magnitude of negative shear angle. In the case of rake angle of 30° the magnitude of positive shear angle was larger than that of initial negative shear angle. The magnitude of initial negative shear angle was reduced in the coated cut, which seemed to be a factor of reducing the burr size. As the depth of cut increased, its increase ratio was reduced.

Figures.10~12. shows the distance between tool and end of workpiece with the rake angle for each depth of cut. The larger rake angle is, the smaller distance between tool and the end of workpiece is. The effect of surface environment in coated cutting became larger with the decrease of rake angle. The reduction ratio of 0.03mm depth of cut was larger than that of 0.1mm depth of cut. The tendency was more remarkable in the fine cutting. Fig. 13~16 shows the relation between burr thickness and depth of cut according to the rake angle of 0°, 10°, 20°, 30°. The burr thickness was measured with a profile projector. The burr thickness increased with the increase of depth of cut, but the burr thickness was decreased with the increase of the rake angle and the tendency of increase of burr thickness declined in the coated cut at the same cutting condition. Especially, the effect of surface environment was remarkable in the case of smaller rake angle.

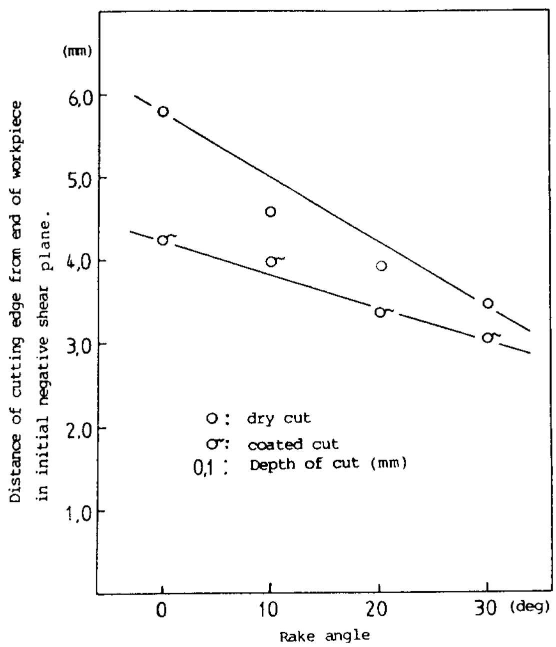


Fig. 12 The relation between distance of cutting edge from end of workpiece in intial negative shear plane and rake angle

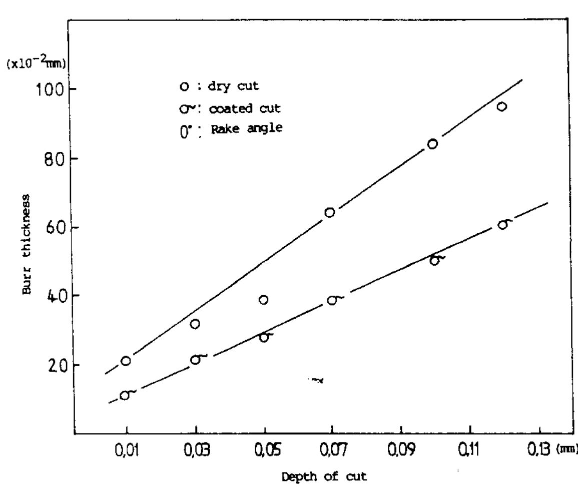


Fig. 13 The relation between burr thickness and depth of cut

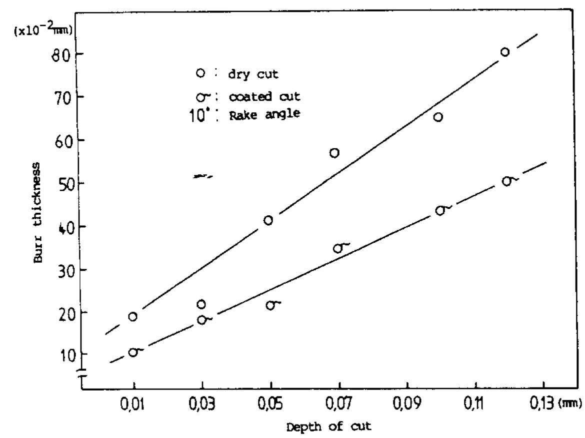


Fig. 14 The relation between burr thickness and depth of cut

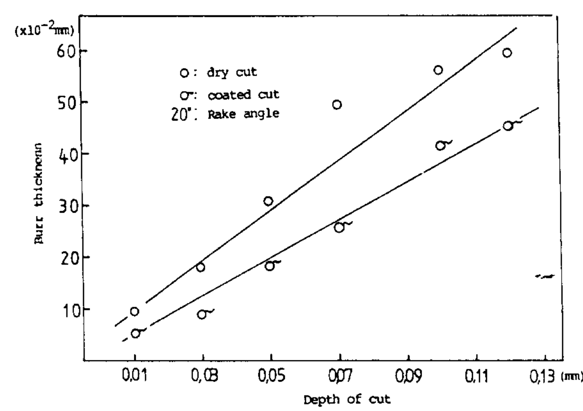


Fig. 15 The relation between burr thickness and depth of cut

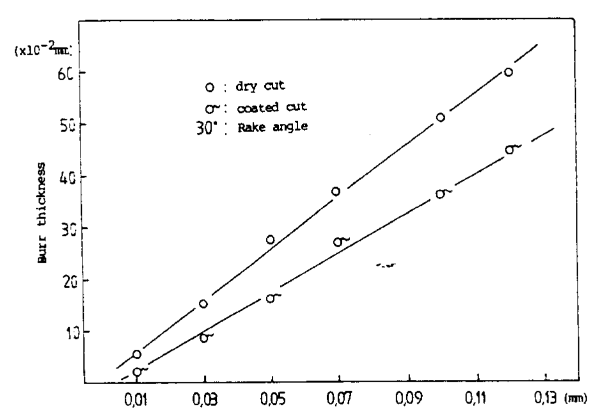


Fig. 16 The relation between burr thickness and depth of cut

5. CONCLUSIONS

On this paper, the orthogonal cutting tests were performed to investigate the burr formation mechanism near the end of cut by using a copper under the condition of polar organic environment. From the results of burr formation experiment, the following conclusions are obtained:

(1) As the depth of cut increased, the rake angle decreased, resulting in large burr size. When the polar organic substance was coated on the end face, burr forming ratio decreased remarkably.

(2) Positive shear angle increased with the increase of depth of cut and rake angle. On the contrary, the magnitude of initial negative shear angle increased with the increase of the depth of cut, but reduced as the increase of rake angle. The effects of polar organic substance coating for the smaller rake angle and depth of cut was more obvious.

(3) Burr size depended on initial negative shear angle and the distance between initial negative shearing point and the end surface of workpiece.

(4) The polar organic substance coated near the end surface reduced the burr size.

From these results, machinability can be improved by coating the work with polar organic materials, and also burr size reduction in coated cut can be obtained.

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