# Study on Micro Diameter Drill Working

## – Effects of Working Conditions on Burr and Cutting Force –

Akira Sugawara

The Research Institute for Scientific Measurements

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Synopsis

This work was studied for the influence of working conditions; drill point shapes, drill feed, cutting speed, workpiece structure on burr in plastic deformation and cutting force in micro drilling.

The results are as follows; Drilling with duller shaped drills causes to form remarkable burr. Burr weight in micro drilling, however, in spite of extremely dull condition of drill point shapes, has a tendency of decreasing in workpiece with larger crystal grains and minute cut depth. And cutting force in drilling of same feed becomes larger in the case of drilled part characterized with large number of crystal grains. As the reason of these phenomenon in micro drilling, the effects of crystal structure in workpiece and micro protrusions on lip are considered, because of the speciality for the minuteness of drilled shapes and units.

## I. Introduction

In the cases of small worked shapes, following facts in which cutting view point of large worked shapes does not occasionally applied to small worked shapes are; 1. Though the number of drill revolution has to be increased with the decrease of drill diameter, generally, high speed revolution is not recommended in practical drilling.[1) ] 2. In small diameter punching, punching the hole with smaller diameter than workpiece thickness.[2)] These characteristic causes are considered to be the internal and external effects concerning with micro structure in workpiece and drilling conditions which might have not to be considered in the cases of large worked shapes. This report is described in detail to the above-mentioned effects on burr formation and cutting force in micro drilling with various workpieces and different drills, by aimming the burr which is formed around the drilled hole in drill working.

## II. The cutting ability

A burr is formed around the drilled hole as shown in Fig.1. An ideal drilled situation of the hole in which burr does not formed is the process realized with drilling part removed as chip completely. Working quality of this situation is termed Wi, an ideal working quality of shear. When chip weight and burr weigh represented as Ws and Wp respectively, relation of Wi, Ws and Wp consists of the equation that Wi is the sum of Ws and Wp. Wi is calculated from average diameter of the drilled hole and thickness and specific gravity of the workpiece. Ws as chip weight is calculated by subtracting workpiece weight after working from the weight before working. After Ws and Wi are calculated, the ratio of Ws to Wi was defined as cutting ability, the heigher ratio means the heigher cutting ability with little burr.

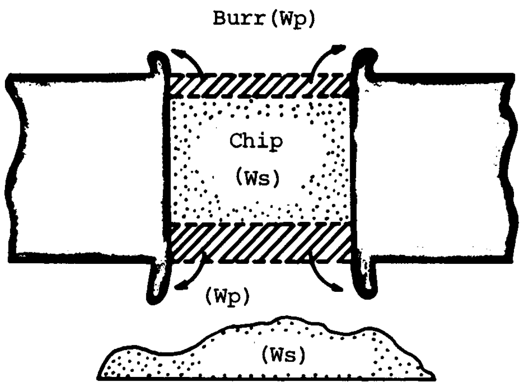


Fig.1. Sectional shape of the drilled hole

In comparing drilled shapes by variously size drill on basis of cutting ability, it is important to equal the drill diameter to the workpiece thickness. By this adjustment, the comparison of the drilled situation is made possible independently of the sizes of drilled holes.

Workpiece weight is measured by electric balance before and after drilling, Wi-weight in micro drilling is very minute value as shown in Table 1. Accordingly it is necessary to make a size of workpiece as small as possible, and to measure workpiece weight as precisely as possible before and after drilling.

Table 1. Ideal working quality of shear in drilled hole

| Diameter of drilled hole ( mm ) | Ideal working quality of shear ( mgf ) |
|---|---|
| 1.0 | 6.18 |
| 0.5 | 0.773 |
| 0.25 | 0.0966 |
| 0.1 | 0.0062 |
| 0.06 | 0.0013 |

## III. Effects of drill point shapes

The twist drills of high speed steel whose diameter are ranged from 0.06mm in minimum to 2.5mm in maximum on the market are used. The shapes of drill points of tools are considered to affect on the cutting ability in variously sized drilling. The consisting element of drill point shapes were checked up in ten drills for the same kind of diameter, and the results are shown in Fig.2. The element of the shapes were defined in Fig.2 as follows; point angle, lip clearance angle, and difference between two lip clearance angles are represented by numerical value of angle, and eccentricity ratio of chisel edge to drill diameter, ratio of web to drill diameter are represented by percentage. Lip shoulder shapes, longitudinal shapes and lip section of drill are drawed in same scale for the purpose of analogical comparison to the different diameter without regard to the drill diameter size.

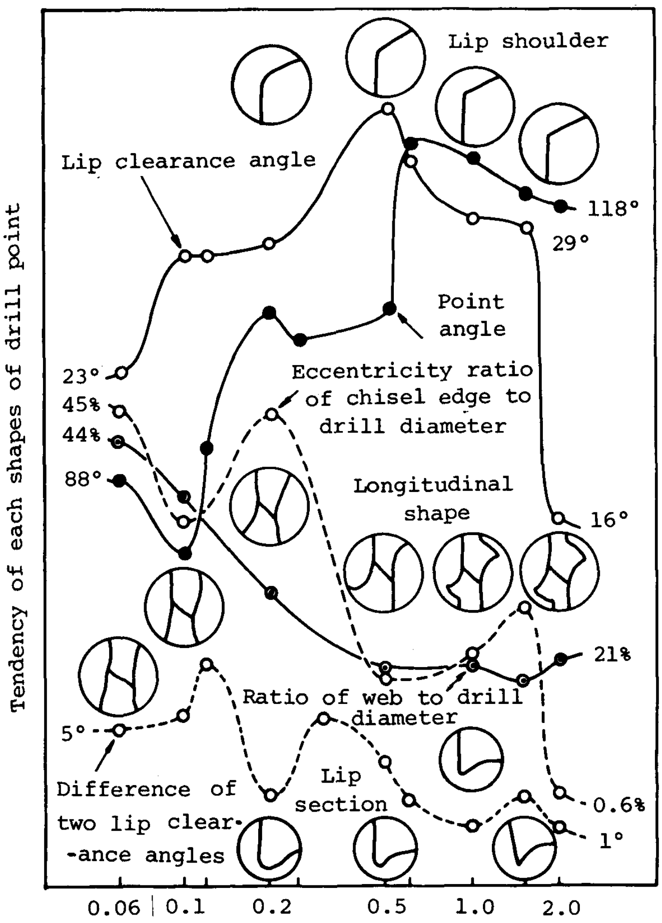



Fig.2. Each shapes of drills with lessening of drill dia.

In Fig.2, each shapes of drill point changes as drill diameter decreases.

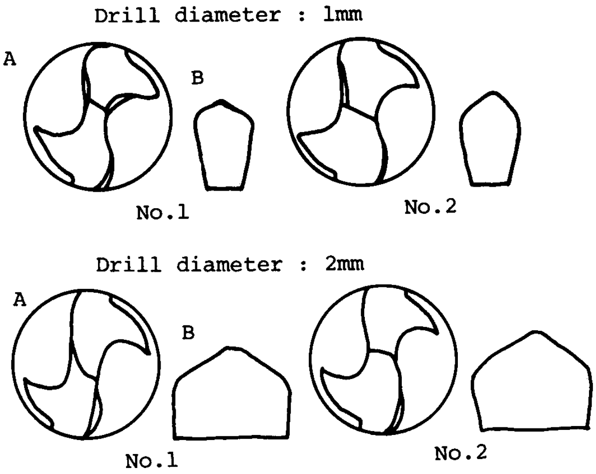
a) The point angle tends to become smaller.
b) The lip clearance angle becomes larger under 2mm diameter, and the difference of two lip clearance angle tends to become larger.
c) The ratio of web to drill diameter becomes larger.
d) The eccentricity ratio of chisel edge to drill diameter becomes larger.
e) Roundish radius of lip edge becomes larger and sharpness of lip is lost.
f) A straight line of lip edge is lost and becomes curved gradually.
g) Roundish radius of lip shoulder becomes larger.

This deterioration of drill point shapes with reduction of the drill diameter, is considered to be due to the size of grinding area in drill point. Larger drills can have sharp shapes because of the largness of their area, however the smaller the drills are the duller the shapes become, because of the decrease of grinding area.

In order to investigate the effect of drill point shapes on the cutting ability, lip and roundish radius of lip shoulder of drills having 2mm and 1mm diameters were transfigured as shown in Fig.3, web and eccentricity ratio of chisel edge to drill diameter in this transfiguration is shown in Table 2. Table 2 also shows these ratios of ordinary drills as well. Table 4 shows the cutting ability in case that drilling was carried out with the method as shown in Table 3. When cutting ability of each drill was compared in this table, the following facts were evident.

When drilling are worked with transfigured drills whose diameter are 2mm and 1mm, the cutting ability becomes worse about 3%, 11% respectively than that of ordinary drills. In order to find out how dullness of drill point shapes affects on cutting ability, the ratio of chisel eccentricity to drill diameter shown in Table 2 and the cutting ability shown in Table 4 are discussed.

The ratio of transfigured drills whose diameters are 2mm and 1mm is 4.6%, which is about eight times heigher than the ratio of ordinary drills. On the other hand, ratio of transfigured drills whose diameter are 1mm is 4.3%, which is about twice of that of ordinary drills. As to the ratio of transfiguration, when 1mm dia.-drill is used, it is smaller than that of transfigured drill with 2mm diameter; the ratio of




A : Longitudinal shape
B : Travers shape

Fig.3. Transfigured shapes of drill point

Table 2. Ratio of chisel eccentricity and web to drill diameters of transfigured and ordinary drills

| Drill dia. ( mm ) | | Web ( % ) | Eccen. of chisel ( % ) | Note |
|---|---|---|---|---|
| 0.06 | | 44 | 4.7 | Ordinary drill |
| 0.1 | | 38 | 3.5 | |
| 1.0 | | 20 | 2.1 | |
| 2.0 | | 21 | 0.6 | |
| 1.0 | No.1 | 21 | 6.4 | Transfugured drill |
| | No.2 | 18 | 2.2 | |
| | Ave. | 20 | 4.3 | |
| 2.0 | No.1 | 21 | 3.3 | |
| | No.2 | 17 | 5.9 | |
| | Ave. | 19 | 4.6 | |

Table 3. Drilling conditions

| | | | |
|---|---|---|---|
| Drill | Drill dia.( mm ) | 2mm | 1mm |
| | Note | Transfigured drills as shown in Fig.3 and ordinary drills | |
| Drilling conditions | Drill rev.( rpm ) | 2000 | 2400 |
| | Drill feed ( mm/min ) | 12 | 8 |
| | workpiece | 0.02%C steel | |

Table 4. Cutting ability in drilling with transfigured and ordinary drills

| Drill dia. ( mm ) | Cutting ability ( % ) | Note | |
|---|---|---|---|
| 2.0 | 94 | Ordinary drills | |
| 1.0 | 93 | | |
| 2.0 | 92 | No.1 | Transfigured drills |
| | 90 | No.2 | |
| | 91 | Ave. | |
| 1.0 | 81 | No.1 | |
| | 83 | No.2 | |
| | 82 | Ave. | |

1mm diameter is 1/4 of that of 2mm diameter. To the contrary, cutting ability of transfigured drills with 1mm diameter decreases about 11% than that of ordinary drills, and its decrease ratio is four times larger than those of drills with 2mm diameter.

This results indicate that dullness of drill point shapes makes burr formation much larger in small sized diameters so as to deteriorate cutting ability.

## IV. Burr formation process with dull point drill

Lip edge and lip shoulder among the drill point shapes at micro drills become extremely duller as shown in Fig.2. When the drilling is made by the use of drills having those shapes, working force is transmitted to workpiece as friction force distributing in wide area including the drilling part; it is not transmitted as shearing force concentrated in lip as in the case of ordinary drills. Model tool, as shown in Fig.4 in which working force is to be transmitted in terms of friction force due to dullness of drill point shapes, is used in trial drilling to investigate the phenomenal formation process of burr in drilling. This model tool forms a remarkable burr, so that it is used in drilling a lead sheet which is sensitive to plastic deformation. Experimental conditions are shown in Table 5.

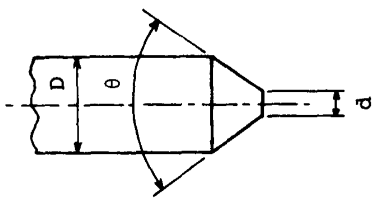



Fig.4. Model tool

Table 5. Experimental conditions in model tool

| | |
|---|---|
| Workpiece | Lead |
| Thickness | 5 mm |
| Model tool | D = 5mm<br>d = 0.8mm<br>θ = 60° |
| Revolution | 5300 rpm |
| Cutting oil | nonuse |

Fig.5 shows the sectional shape of drilled holes when the model tool used for drilling was successively fed 1mm by 1mm in the method

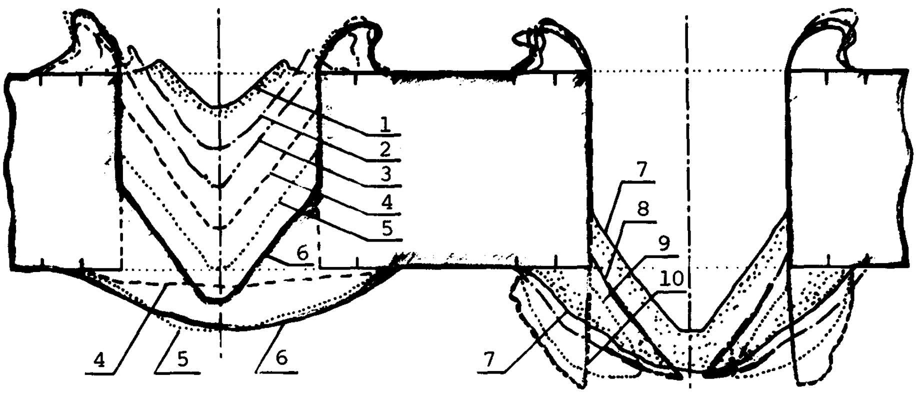



Fig.5. Sectional shape of lead plate in the difference of model tool feed

as shown in Table 5. From this figure, burr formation process in drilling can be surmised as follows.

Most of the workpiece of drilled part may be removed with the drilling action of the first revolution, however, burr formed at this first revolution is pushed out with the burr formed at next revolution to circumferential direction. Burr formation is intermittenty continued according to difference of drill point sharpness until lip shoulder is fed to the interior of workpiece. The underside burr of the workpiece begins to be formed before chisel part reach to the bottom of workpiece, and is intermittenty pushed to circumferential direction responding to sharpness of point form.

The increase of burr formation as shown in this model experiment is considered to be differed from workpiece structure or working conditions. After understanding of this burr formation process, the following experiment was carried out.

## V. Effects of drilling conditions

Drilling was made without center hole and one drill is used only for one drilling in order to avoid the effect of wear of drill point on cutting ability. Drilling was made in wet and hand feed, that is, drill is lift up other while to eliminate chip and then drilling is continued. Table 6 shows drilling conditions such as drill diameter, revolution number, feed speed, etc. Drilling under these conditions is made for investigating the relation of cutting ability to the difference of drill diameters and drilling conditions.

Fig.6 shows the results of drilling carried out by the method as mentioned in Table 6. This Fig.6 shows the following facts with

Table 6. Drilling conditions

| Drill dia. (mm) | Experiment A | | Experiment B | | Experiment C | |
|---|---|---|---|---|---|---|
| | Rev. (rpm) | Feed (mm/min) | Rev. (rpm) | Feed (mm/min) | Rev. (rpm) | Feed (mm/min) |
| 2.5 | | | | | 2000 | 5.79 |
| 2.3 | 160 | 72.38 | 1600 | 7.24 | | |
| 1.1 | | | | | 2400 | 3.19 |
| 1.0 | 360 | 21.33 | 1600 | 4.80 | | |
| 0.6 | 600 | 7.1 | 1600 | 2.66 | | |
| 0.5 | | | | | 2800 | 1.52 |
| 0.25 | 1400 | 0.0746 | | | | |
| 0.2 | | | 1600 | 0.067 | 3800 | 0.028 |
| 0.12 | 3000 | 0.0358 | | | | |
| 0.1 | | | 1600 | 0.067 | 4800 | 0.0146 |
| 0.06 | 6000 | 0.0064 | 1600 | 0.024 | | 0.0064 |

workpiece : 0.02%C steel

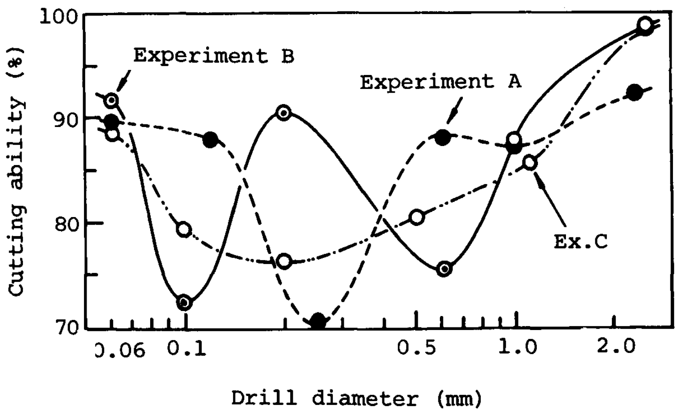



Fig.6. Tendency of cutting ability by the difference of experimental methods

lessening the drill diameter.

In experiment C, cutting ability is fairy good in larger drills, but it becomes worse with the decrease of drill diameter. However, in micro drilling, it becomes better again. In experiment A and B with lessening the drill diameter, cutting ability fluctuates, however, those ability in both cases of micro drilling are considered to be better from qualitative view point of the tendency even though they are not so remarkable as in the experiment C.

The reasons to cause the deterioration of cutting ability with the decrease of drill diameter are considered to be due to the fact as mentioned in III; dull point shapes cause to form larger burr. The reasons to improve cutting ability in micro drilling were not considered to be due to dullness of drill point shapes, accordingly the following drilling conditions are discussed. Though cutting abilities, as shown in Fig.6 were classified on the basis of drill diameter, Table 7 indicates those value classified by cutting speed and drill feed per one revolution. From this table, it is understood that cutting ability becomes worse with the decrease of the cutting speed, nevertheless it becomes better in the region with minute drill feed per one drill revolution. Consequently, goodness of cutting ability in micro drilling was considered to be due to the minuteness of drill feed; minute feed makes drilling part smaller so that it makes transfer of dislocation stimulating the burr formation smaller.

Table 7. Relation of the cutting speed, feed speed per one drill revolution, and cutting ability

| Cutting speed (m/min) | Cutting ability ( % ) | Feed speed (μm/rev.) | Cutting ability ( % ) |
|---|---|---|---|
| 15.7 | 98.5 | 72.4 | 92.2 |
| 12.6 | 98.8 | 21.3 | 87.4 |
| 5 ∿ 9 | 86.6 | 5 ∿ 9 | 95.1 |
| 1 ∿ 4 | 83.9 | 1 ∿ 4 | 82.3 |
| 0.1 ∿ 0.9 | 81.5 | 0.01 ∿ 0.09 | 81.1 |
| | | 0.001 ∿ 0.009 | 89.2 |

## VI. Effect of workpiece structure

In order to investigate the effect of the difference of workpiece structure on cutting ability, workpieces were chosen as follows on the basis of following conditions.

- Crystalline substance
  - Single crystal ———— Iron single crystal ----- Fe(S)
  - Polycrystal
    - Rolling structure ——— 0.02%C steel ------------ Fe(R)
    - Granular structure
      - 0.02%C steel
        - Heat treatment I ------ Fe(H)I
        - Heat treatment II ------ Fe(H)
      - Sintering silver ------- Ag
      - SUS 321 --------------- SUS

1) Burr is easily formed so that cutting ability is easily compared.
2) Effect mixing of impurity on cutting ability is small.
3) The change of thickness does not influence on crystal grain diameter.

As workpiece satisfying the conditions 1) and 2), 0.02%C steel, iron single crystal, were chosen, and as for 3) sintering silver and SUS 321 were chosen. They are represented by the symbol shown at the end of each workpieces. The average crystal grain diameter of these workpieces are as follows; Fe(H)I = 30.5μm, Fe(H)II = 28.7μm, Ag = 15.6μm, SUS = 2.3μm.

Drilling was carried out by hand feed, using cutting oil, without center hole drilling. In order to make the effect on cutting ability caused by abraision small, one drill was used only for drilling one hole. Drilling conditions of this experiment are shown in Table 8.

Table 8. Working conditions in drilling

| Drill diameter ( mm ) | Revolution ( r p m ) | Feed speed ( mm/min) | Workpiece (Correspond to drill dia.) |
|---|---|---|---|
| 2.5 2.0 1.8 | 2000 | 11.58 | [Fe(R),Fe(H)],SUS,Fe(s) |
| 1.5 1.1 1.0 | 2400 | 7.68 | Fe(S),[Fe(R),Fe(H)],SUS |
| 1.0 0.5 | 2800 | 4.26 | Fe(s),[Fe(R),Fe(H),SUS |
| 0.41 | 880 | 4.26 | Ag |
| 0.32 | 1130 | 0.1074 | Ag |
| 0.3 0.25 0.2 | 3800 | 0.1074 | Fe(S),SUS,[Fe(R),Fe(H),Ag] |
| 0.41 0.32 0.17 | 3800 | 0.1074 | Ag |
| 0.1 0.05 | 3800 | 0.1074 | Ag |
| 0.17 | 2120 | 0.1074 | Ag |
| 0.1 | 3800 | 0.1074 | Ag |
| 0.1 | 4800 | 0.0702 | Fe(S),Fe(R),Fe(H),SUS |
| 0.06 0.05 | 6000 | 0.0386 | [SUS,Fe(R),Fe(H)],Fe(S),Ag |

These conditions were determined by following reasons.

1) Though the number of drill revolution must be increased with the decrease of drill diameter, generally, high speed revolution is not recommended in practical working, accordingly, the maximum revolution number was determined to be 6000rpm. As to the relation between drill diameter and the revolution number, Levin's recommend value[3)] was used, consequently, in case of drills whose diameter do not have so much difference, drilling was performed at the same revolution number.
2) Drill feed was made in the same working condition that produces chip continuously. With the drill that has the same revolution and the similar drill diameter, drilling was made in the same feed speed.
3) Since recommended working condition of Ag is unknown, workpiece was drilled in constant peripheral velocity and constant revolution as was shown in Table 8. As cutting ability shows the same tendency, the latter result of drilling was shown.

Fig.7 shows cutting ability caused by the difference of drill diameter and workpiece structure, when each workpiece was drilled in the drilling conditions as shown in Table 8. As the influence of crystal orientation of drilled area in drilling on single crystal was not evident, the average of experimental results in three directions was shown in Fig.7. According to this figure, cutting abilities of each workpieces are classfied into three tendencies, with lessening of drill diameter.

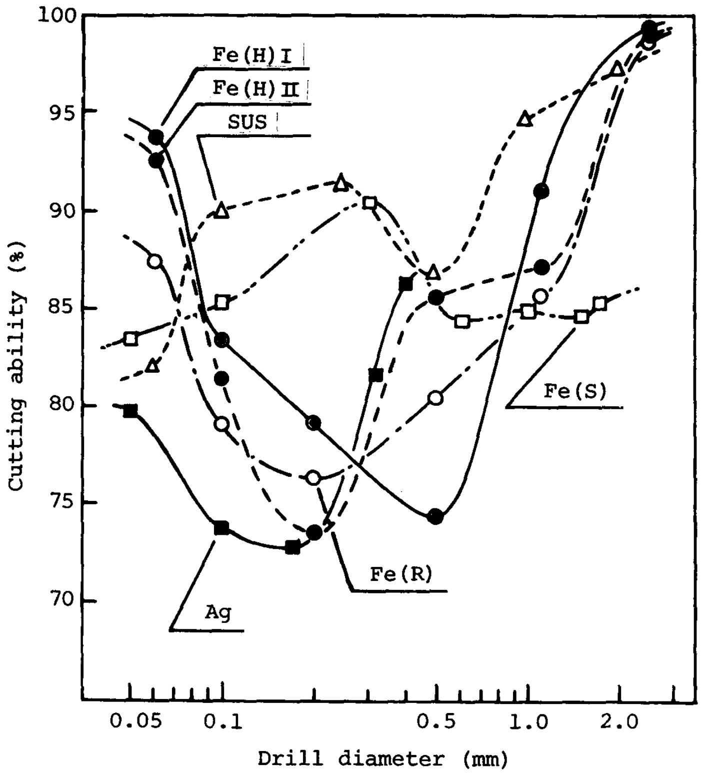



Fig.7. Cutting ability of each workpieces with lessening of drill dia.

1) Remarkable change was not perceptible: Fe(S).
2) Cutting ability becomes worse gradually, and shows minimum at certain diameter, however, it becomes better again as drill diameter lessens more: Fe(H)I, Fe(H)II, Fe(R), Ag.
3) Cutting ability becomes worse gradually: SUS

These tendencies are discussed in detail as follows.

## VI-1. Cutting ability of Fe(S)

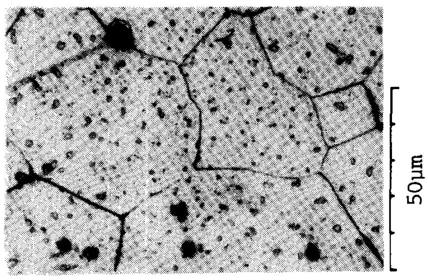
As to cutting ability of Fe(S), 0.3mm diameter drill shows several percent better than other diameter drill, nevertheless cutting ability shows constant tendency regardless of difference of drill diameter. The cause was considered as follows.

In workpiece Fe(S), transfer of dislocation and subsequently restriction ot plastic deformation is small, because it has no crystal boundary. Consequently, regard less of sharpness or dullness of drill point shapes, the effect to make plastic deformation produced only on the part of drill point or partly on drilling part is to meet the fact that dislocation will inevitably transfer to the outside of drilled part and plastic deformation area spreads. Consequently, no concentration of stress around the drilled part is evinced and plastic separation is difficult to occur in that part. Accompanying this plastic deformation, workpiece in drilled part is pushed outside of that part. The result explains well that, despite of the difference of drill diameter, burr area is relatively large and cutting ability is constant.

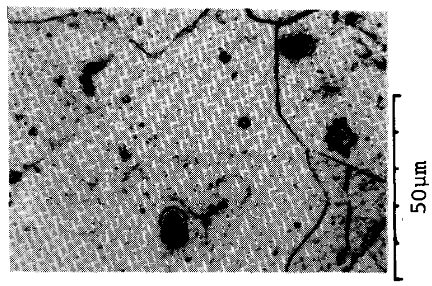
### VI-2. Cutting ability of Fe(H)I, Fe(H)II, Fe(R), and Ag

Cutting ability of these workpieces shows similar tendency with lessening of drill diameter. That is, cutting ability reaches the minimum value at certain drill diameter; Dmin[Fe(H)I : Dmin = 0.2mm, Fe(H)II : Dmin = 0.5mm, Fe(R) : Dmin = 0.2mm, Ag : Dmin = 0.17mm]. In case of thicker drills, cutting ability decrease with the decrease of diameter, on the contrary, with further decrease less than Dmin diameter, cutting ability increases owing to the decrease of diameter. The tendency is evident only in drilling workpiece with relatively big crystal grain such as workpieces mentioned above. Consequently, this phenomenon is considered to depend on the size of workpiece's crystal grain. And the micro structures of Fe(H)I and Fe(H)II were investigated, which show remarkable improvement of cutting ability. In relation the influences on cutting ability with drill diameter is considered.

As shown in Photo.1, in the microphotograph of Fe(H)I and II, size of crystal grain is uneven, small crystals scattering around big one. It is natural, when the heat treatment temperature and process of grain growth are taken into account, however this phenomenon is remarkable in Fe(H)II. In magnifying these microphotographs of each steel thickness with a projector, the number of crystal in measuring area (0.125mm x 0.085mm) was counted, and then the area of the biggest crystal and the length of grain boundary were measured. From these measuring results, the number of crystal grain in drilling part (drill radius scquared x pi) in drilled workpiece, average diameter of crystal grain, length of grain boundary and ratio of grain occupancy mentioned later are calculated. And these properties of Fe(H)I and Fe(H)II are shown in Fig.8. Each value at thickness of 0.06mm, however, is presumed from the value at thickness 0.1mm. Cutting ability of these workpiece and the number of crystals which included in drilling part of SUS and Ag are also shown.




a : Fe(H)I




b : Fe(H)II

Photo.1. Microphotograph of Fe(H)I and Fe(H)II [Thickness : 2mm]

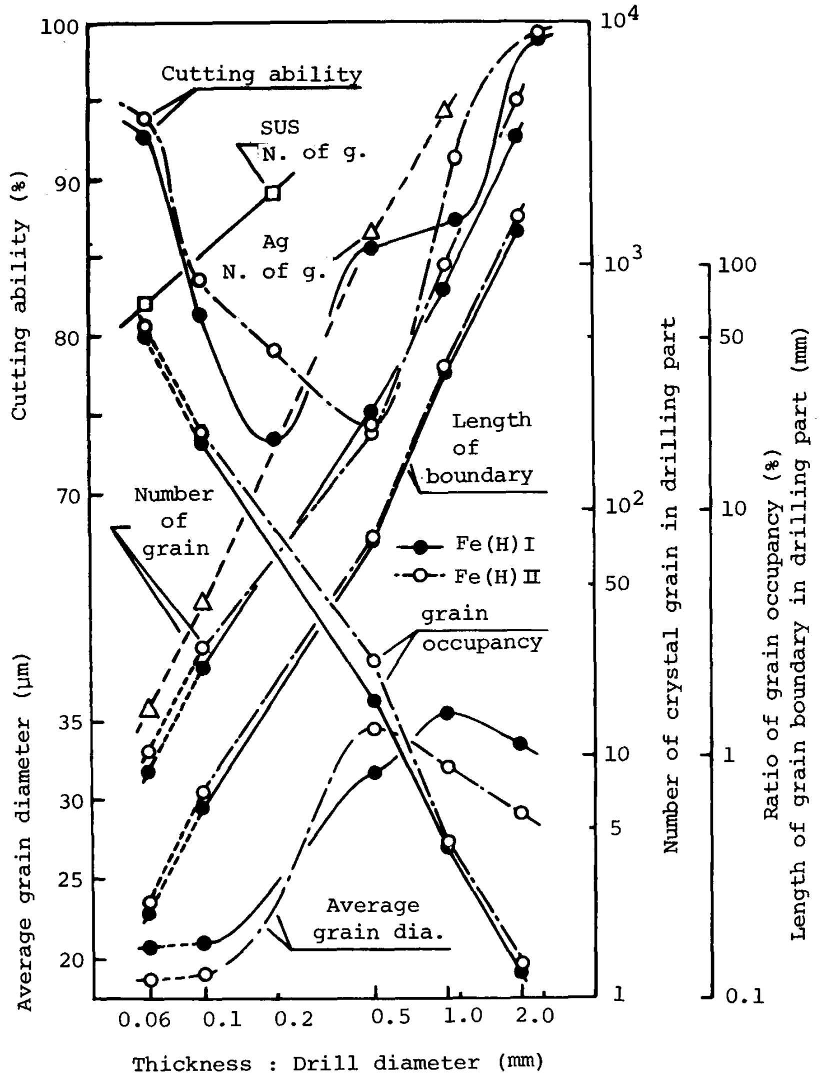



Fig.8. Property in each thickness

Ratio of grain occupancy was defined as the ratio of the biggest occupying area of crystal grain in the measuring area depending on a method of estimation of such structure having uneven size of crystal grains as shown in Photo.1 in relation with diameter.

Fig.8 shows following facts. Although the number of crystal grain in drilling part and length of grain boundary decrease with lessening of drill diameter, the ratio of grain occupancy of workpieces becomes larger gradually. Cutting ability becomes better in drilling (drilling on thinner steel) with thinner drill used in this complicated area. The relationship between drill diameter and cutting ability is considered from the above results.

VI-2-1. Cutting ability within the drilling diameter larger than Dmin

In ideal drilling, working force as shearing force concentrated on drill point works on workpiece so as to cause plastic deformation. In case of drilling with large diameter, such cutting is considered to occur with reducing drill diameter. However, shapes of drill point become worse as shown in Fig.2 with lessening of diameter. Working force is transmitted to the workpiece not as concentrated stress but as friction force distributed on the surface, as is shown in a drilling experiment with an model tool described in the section III. In this case, crystal grains of workpiece become smaller compared with the diameter as shown in Fig.8 and restrict each other. Accordingly, restricted plastic deformation around the drilled part becomes impossible, and plastic deformation area spreads to the outside of the drilled part and cutting ability decreases. This is the opposite tendency to the case of Fe(S) described in the section VI-1.

VI-2-2. Cutting ability within the extent of smaller diameter than Dmin

In these extents, in order that diameter becomes smaller, the size of workpiece crystal approaches to the drilling diameter, and crystal boundary included in drilled part decreases, which makes plastic deformation easy in the drilled part on account of the same reasons for plastic behavior of Fe(S) mentioned before. Meanwhile, because of crystal boundary that intercepts plastic deformation around the drilled part, spreading out of plastic deformation area is prevented by its restriction.

This can be explained that plastic strain concentrates around the drill. Accordingly in this part plastic separation is liable to occur and cutting ability increases. This mechanism can be applied in explaining plastic behavior in Fe(R) and Ag with relatively large crystal. The tendency of cutting ability of Fe(R) with diameter larger than Dmin of rolling structure, is considered to be under the influence of subdivision of crystal caused by rolled working, besides the reasons stated before.

VI-3. Cutting ability of SUS

In case of drilling on SUS, shapes of drill point becomes duller with lessening of drill diameter as well. While cutting ability decreases by the same reasons stated in VI-2-1 that causes to reduce drill diameter to Dmin. However in this case, the size of crystals included in drilling part is very minute as shown in Fig.8, so that even drill diameter becomes small, the crystals are numerous. Consequently, the phenomenon that diameter is smaller than Dmin as stated in VI-2-2 is not observed, while cutting ability decreases monotnously.

## VII. Effects of crystal structure of workpiece

### VII-1. Effect of crystal boundary

In case that drilling part exists among the crystal grains different in size, the effect of the size of crystal grains on the area susceptible to plastic deformation is considered as shown in Fig.9. The plastic deformation is considered to be the transfer of dislocation and the crystal boundary prevents this transfer, accordingly, when the same sized feed is given at the same drill diameter, the area susceptible to plastic deformation becomes larger in Fig.9A, and smaller in Fig.9B.

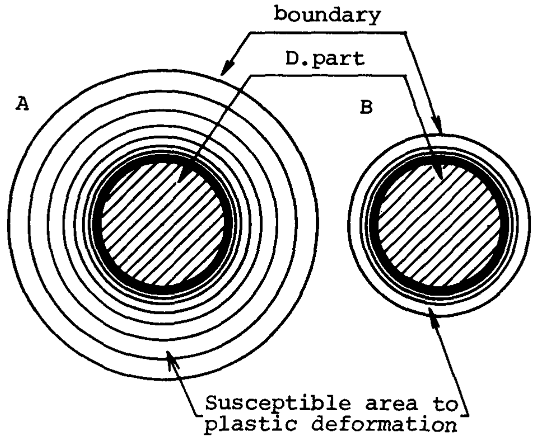



Fig.9. Model of plastic deformation area by the difference of crystal grain size

For this experiment, a model tool as shown in Fig.4 is used, so as to make the plastic deformation bigger. The dimension of D and d in this case is fixed to be same as the diameter of 0.2mm and its web size. The point angle is set to be 60°. The model tool is made from piano wire.

As a workpiece for this experiment 0.02%C steel is chosen, and the size of crystal grains in workpiece is necessary to enlarge as large as possible so that the slip line is easily to be observed. As shown in Photo.2, the size of crystal grains were regulated by pressing process and heat treatment repeatedly; in the larger grains the larger diameter was fixed to be 0.3mm.

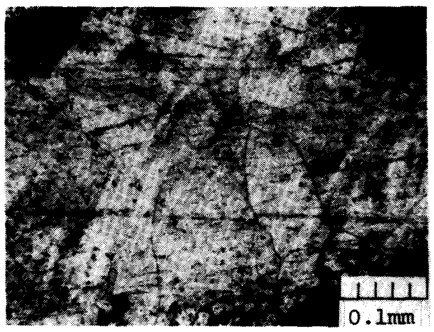



Photo.2. Heat treatment structure of 0.02%C steel

The microphotographs of drilled part were shot before and after drilling. In examing the drilled workpiece and the number of crystal grains, the observation of slip line within the crystal grain was carried out as well. Nevertheless, the slip line is rather difficult to be observed on the drilled part because of burr around the drilled hole. Accordingly, in suspending the feed of model tool, the slip line was observed on the side of exit of drilled hole.

In case that drilling was interrupted by the method as mentioned above, burr began to be formed on the reverse side of workpiece, and accompanied to it, slip lines are observed within the crystal grains of drilled part, as shown in Photo.3. The direction of model tool revolution runs from crystal grain A to crystal grain C, and the part looked white in the middle of black part indicates the highest part of burr.

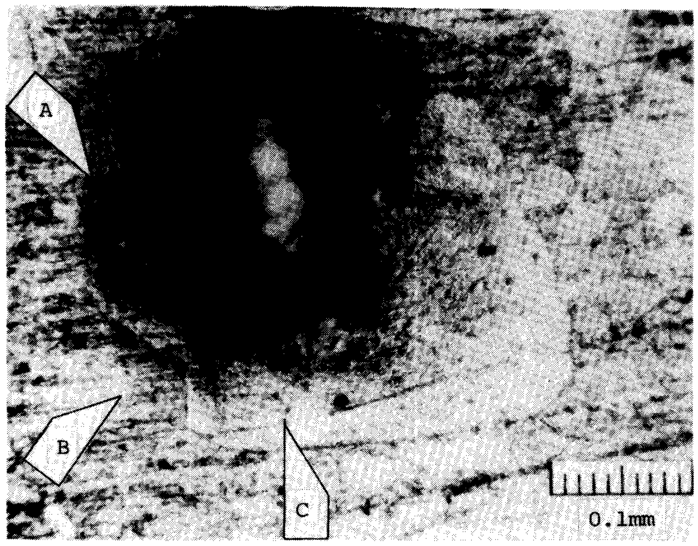


Photo.3. Effect of crystal grain boundary

The slip lines in the crystal grain A run numerously toward the drilled direction, filling the crystal grain boundary to the limit. However, in crystal grains B, which has not been worked yet, slip lines are not observed. Because of the suspension of feed to model tool, the crystal boundary between the crystal grain A and B prevents the expansion of plastic deformation within the crystal grain A. The slip lines within the crystal grain C, the working object, are not so thick as those observed in the crystal grain A, for in the former the grain size is larger, and they spread extensively to the crystal boundary.

From these observations of slip line, the following is concluded; as was presumed in Fig.9, the area susceptible to plastic deformation exists in the crystal grain a part of which is contained in drilled part. When the crystal grain is large, the slip lines extend to the crystal boundary, while in the smaller grains they gather in a narrow area.

VII-2. Effect of crystal anisotropy

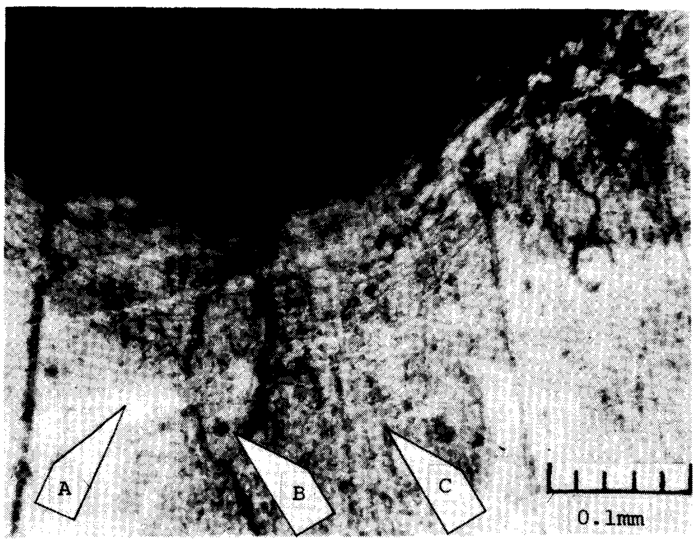


Photo.4. Effect of crystal anisotropy

Photo.4 is the photograph of the reverse side of workpiece drilled by the drill whose diameter is 0.2mm. Around the drilled hole which looks black, a lot of slip lines forming contour lines are observed within the crystal grains A and C. However, in the crystal grain B existing between A and C, whose larger diameter is about 0.1mm, and shorter one 0.05mm, no slip line is observed.

The reasons can be pointed out as follows: the crystal grains A and C, part of which are contained in the drilled part, respectively, has a larger area, accordingly it has a larger area susceptible for plastic deformation, as was pointed out in VII-1. However, in the crystal grain B, which is not contained in the drilled part, the working process had been finished before the sufficient working stress was stored; which would depend on its slip direction different from those of A and C.

## VIII. Effect of minute feed

### VIII-1. Effect of the difference of the number of crystal grains in the drilled part and that of feed on cutting force

The micro torque-thrust measurement apparatus shown in Fig.10 was manufactured mainly for this experiment. The characteristics of this apparatus are : by the aid of 2 steel ball it can be separated into the upper part and the lower part, and, by adjusting the distance of 1 and 3 doughnut shaped magnets standing opposite each other, can reduce the upper load almost the 0 through the magnetic resistance so as to make the measurement of minute torque possible. Thrust was measured by 4 , while torque was measured by 5. As is shown in Photo.5, the experiments were carried out after this apparatus was fixed on the working table of jig borer. The revolutions of tool to 3000rpm utilized the revolution of jig borer, and those over 3000rpm employed the air turbine for jig grinder. 5 is a variable feed apparatus that can move the working stand of the micro torque-thrust measurement apparatus vertically.

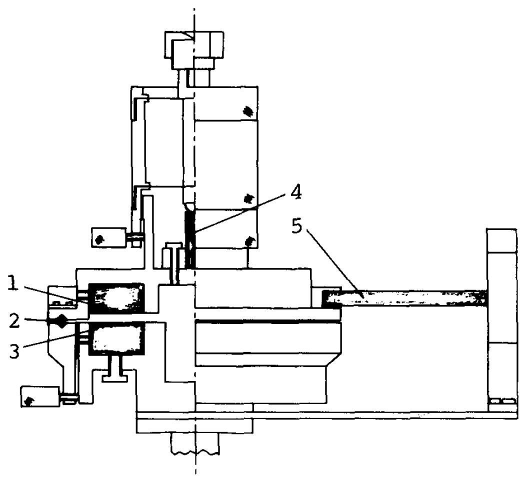



Fig.10. Measurement apparatus of minute torque and thrust

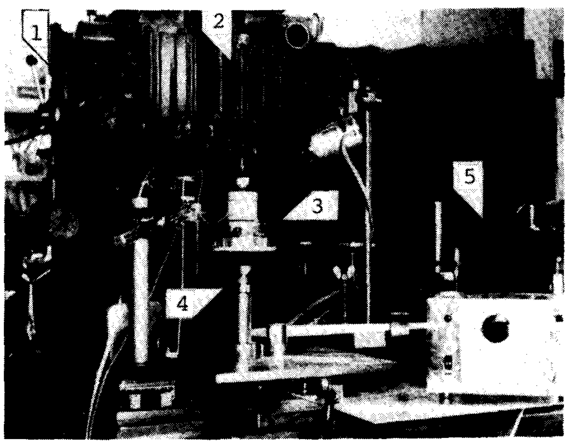



Photo.5. Experimental apparatus

The tool feed was fixed to be 0.075mm/min at 5 feed apparatus shown in Photo.5. In order to maintain the cut depth per one drill revolution the same as that of 0.2mm diameter drill as shown in Table 8, the revolution number of the tool was regulated to be 3000rpm. In order to change the depth of cut per one revolution for this experiment, the revolution number of tools was changed.

The results of the experiment are shown in Table 9. Concerning the reduction of the depth of cut per one revolution and the variation of cutting force, the case of drilling of 4 crystal grains in drilled part is examined.

Table 9. Effect which the difference of crystal grain number in drilling part and feed speed per one drill revolution affect on the cutting force

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Drilling condition | Revolution ( r p m ) | 3000 | | | 8000 | 22000 | |
| | Feed speed ( μm/rev.) | 0.025 | | | 0.0094 | 0.0034 | |
| Model tool and drill diameter are 0.2 mm | | Model | Drill | | Model tool | | Drill |
| Cutting force | Thrust ( gf ) | 357 | 98 | 137 | 110 | 67.3 | 44.3 |
| | Torque ( cm-gf ) | 5.85 | 4.15 | 5.54 | 4.55 | 4.53 | 2.70 |
| Number of grain in drilling part | | 4.3 | 4.7 | 69 | 2.7 | 3.3 | 4.3 |

In case that the revolution number becomes 7 times bigger, from 3000rpm to 22000rpm, and when the depth of cut is reduced to 1/7, the changes of cutting force of model tool and drill decreases to 0.2 and to 0.5, while the reductions of torque are 0.8 and 0.7; the reduction of thrust of model tool is far greater. Consequently, the smaller the depth of cut per one revolution is, the smaller the cutting force becomes.

As to the relation between the number of crystal grains, the object of working process, and the cutting force, in drilling by 0.2mm diameter drill, when the average number of crystal grains in drilled part becomes approximately 12 times, that is, 4.7 grains multiply to 69 grains, the increases of thrust and torque are approximately 1.6 and 1.3 times. The reason is considered to be as follows; in this experiment the difference of working condition is the increase of crystal grain number, so that the effect of crystal anisotropy augments so as to necessitate the greater working force.

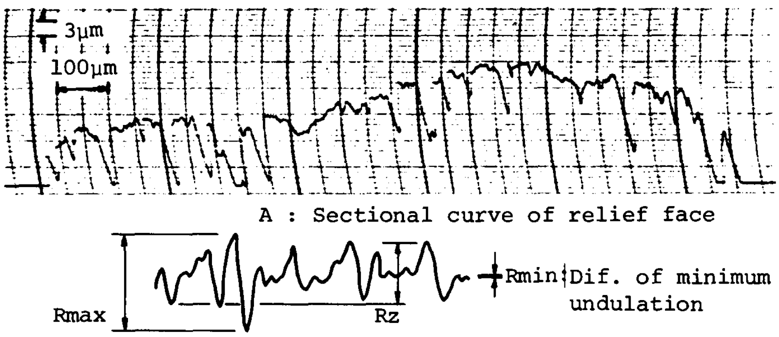
## VIII-2. Effects of minute feed and surface roughness of lip edge

Generally speaking,[4] because lip edge of working tools does not have an ideal straight line but roundish radius, in the depth of cut shallower than this roundish radius, the phenomenon of sliding occurs so as to obstruct cutting.

From Table 9, the decrease of depth of cut in this experiment is evident; it reduces from 0.025μm to very minute cutting of 0.0034μm. According to the above established theory, unless roundish radius of lip edge is formed under these values, cutting is impossible. The formation of these values, however, is almost impossible as well.

This experiment is carried out on the working hypothesis that the very minute cutting depends not on the sharpness of lip edge but on the phenomenon in which the minute projections making surface roughness become lips respectively.

As the measurement of surface roughness of drill lip edge is very difficult, lip shoulder is presumed to be cut off under the same condition as lip edge, micro cutting is considered on the basis of lip clearance face of 5mm diameter drill. Fig.11 shows the sectional curved line of lip clearance face around lip edge of 5mm diameter drill. When the measurements of depth of cut are equal to the surface roughness 6.2μm Rmax and 4.4μm Rz, according to this figure, each minute protrusion does not interfer with cutting but makes friction contact with workpiece. As is shown in Fig.11, the smallest difference between minute protrusions is defined as the difference of minimum undulation Rmin. In Fig.11, Rmin is about to 0.1μm, in drilling of micro cutting made under this value, minute protrusions become lip edge individually, which makes micro cutting, possible and as Table 9 indicates, cutting force smaller.




A : Sectional curve of relief face

B : View of the difference of minimum undulation

Fig.11. Sectional curve of relief face in the vicinity of lip edge whose drill diameter is 5 mm and view of the difference of minimum undulation

## IX. Characteristics of burr formation in micro drilling

In micro drilling, as was mentioned in the sections VI to VIII, the size and number of crystal grains in drilled part, the crystal boundary, and the cut depth of micro cutting influence each other so as to reduce burr and cutting force. The effects of these mutual influences are regarded as great in micro cutting. From discussion in this report, working situation depending on the difference of drill diameters are classified in Table 10.

Table 10. Difference of working conditions depending on difference of drill diameters

| Cause | Sub-group | Working conditions \ Drill | Drill of micro dia. | Drill of small dia. (dia. 0.2mm – dia. 2mm) | Drill of large dia. |
|---|---|---|---|---|---|
| External cause | | Quality of point shape | dull | fairly sharp | sharp |
| External cause | | Effect of tool point shape | minute | small | big |
| External cause | Depth of cut per one drill rev. | cut depth | Under surface roughness of lip edge | Within roundish radius of lip edge | Over roundish radius of lip edge |
| External cause | Depth of cut per one drill rev. | Relation between lip and depth of cut | Minute protrusions among surface roughness become lips so as to enable micro cutting | Liable to sliding ; because of dull point shapes, cutting force tends to transfer to workpiece as frictional force | Working force depends on sharpness of lip edge ; it is transmitted to workpiece as shearing force |
| Internal cause | | Ef. of grain size, boundary | big | small | minute |
| Internal cause | | Ef. of aniso. of grain | small | | big |
| Internal cause | | Effect of micro cutting | big | small | minute |
| Burr tendency | | | small | big | small |

As Table 10 indicates, in micro diameter drilling, the effect of tool point shape is very small. Since the depth of cut per one revolution and drilled part is very minute, however, such micro structure as to be disregarded in an ordinary drilling makes the effect of micro cutting greater so as to lessen burr formation.

## X. Summary

This experiment was investigated for the influence of working conditions; drill point shapes, drill feed, micro structure in workpiece on burr formation and cutting force in micro drilling by drilling various workpiece with different drills. The results are as follows:

1. In case that drill point shapes of twist drills on the market were compared with each other, the shapes become duller with the

decrease of drill diameter. And this dullness of shapes causes to form larger burr formation.

2. In poly crystal with relatively large crystal grains, the number of crystal grains included in drilling part becomes small, while the effect by slip prevention caused by crystal anisotropy decreases. Accordingly, drilling part becomes sensitive to plastic deformation caused by working force. However, because crystal grain boundary of each crystals exists adjacent to drilling part, plastic flow is prevented and plastic separation easily occurs. Micro cutting is performed with minute feed requires short transfer in dislocation, which is thought to be one reason to form smaller burr.
3. In single crystal, crystal boundary which prevents the transfer of dislocation is nothing and extent of plastic deformation becomes large, so that burr becomes relatively large and constant independent of the change of working diameter.
4. In drilling on the workpieces with the same diameters, cutting force becomes larger in the workpiece having more numerous crystal grains in drilled part.
5. In case that the depth of cut per one revolution is very minute, minute protrusions among surface roughness of lip edge become lip edges individually so as to enable the micro cutting.

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