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# Deformation Work in Abrasive Cutting

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#### Abstract

In order to investigate the complicated behavior of material beneath a groove formed by abrasive grain cutting, a single grit cutting test was performed with a modified cutting tool which was determined statistically. In our experiment a conical tool having an apex angle of  $90^{\circ}-160^{\circ}$  was used. To observe the deformed zone beneath the groove, a cross section of the work material beneath the groove was obtained by using a micro-cutter. Then the hardness of the deformed zone was measured in three plaines, i.e, at the surface, at the cross section along the cutting direction and at the cross section perpendicular to the cutting direction.

Besides, a compression test was performed and taking the relation between stress and strain and that between strain and hardness into consideration, the deformation work beneath the groove was obtained experimentally. Then it was compared with the total work necessary to form a groove which was calculated from the cutting force.

As a result it was found that there were two types of the deformed zone, i.e, a cutting type and a compression type as well as in the case of an indentation test. The ratio of the deformation work to the total work expended in forming a groove with a conical tool depends on the apex angle of the tool and the ratio varies from 0.2 to 0.7 in this experiment.

#### 1. Introduction

Although the chips are formed in abrasive cutting, the deformation work absorbed in the work piece during cutting should be greater than that in the case of orthogonal cutting, because of its large negative rake angle. The facts that the ratio of the vertical to the horizontal components of the cutting force in abrasive cutting is of the order of 2, whereas it is 1/2 in orthogonal cutting, and the existence of large swell out phenomena proves the significance of the deformation work in grinding. These considerable large forces and the high temperature genarated in the interface between workpiece and abrasive tool are considered to bring about the low quality of the finished surface.

In order to clarify the basic mechanism of surface generation in the grinding process, the behavior of metals in abrasive cutting must be recognized. However, it is too complicated to describe comprehensively because of the random and complicated structure of grinding wheels. Therefore it becomes more important to get information about the fundamental operation of individual abrasive grits.

This paper is concerned with the deformation work in single grit cutting. In the experiment, one pass cutting with a modified abrasive tool was performed. The

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deformed region was obtained by means of Vickers hardness test and the deformation work beneath the groove was calculated from the data of compression tests. The cutting forces was measured with piezo-electric elements and the total energy needed to form a groove was calculated.

It is the main purpose of this paper to show how much energy is absorbed as the deformation work beneath the groove in abrasive cutting as well as to make clear how the extent of the deformed zone is influenced by the shape of modified tools.

#### 2. Experimental Procedure

### 2.1 Cutting apparatus and conditions

The experiment was performed with a surface grinding machine tool (OKA-MOTO CO. PSG-IAE). The basic apparatus consisted of a single modified tool fastened to a steel wheel mounted on a grinding wheel spindle. The rotating cutting tool operates at nominal grinding speed of 1700 m/min. on a workpiece mounted on the surface of the grinding machine table having cross speed of 5 m/min. Only a groove was cut within a depth of 10-50  $\mu$ .

The modified cutting tool was determined to be conical having an apex angle of  $100^{\circ}-160^{\circ}$  referring to the reports<sup>1) 2)</sup> concern with the profile of the abrasive cutting edge, which had investigated the shape from scratching traces, determined the shape of the cutting edge from the components of cutting force or observed it directly with a microscope. The modified cutting tool was made of cemented carbide and the workpice material was S55C steel which was annealed at a temperature of 790°C during 1 hour in vacuum atmosphere.

# 2.2 Measurement of cutting force

Forces acting in the cutting process have been measured as follows. For the acurate measurement of the short duration impacts, it is essential for the dynamometer to possess a very high natural frequency. Then, in this experiment, a dynamometer which utilizes piezoelectric elements was used to measure both the horizontal and the vertical components of cutting forces. Each element is silver coated on both faces and on both ends to collect the charges generated by the cutting forces. These elements were connected to a dynamometer with a natural frequency of 30 K Hz. The signal from the dynamometer during cutting was taken out through a memorytype synchroscope and recorded with a camera. The force measurement set up is shown in Fig. 1(a).

As two components of the cutting force act upon the dynamometer at the same time, the response of each of them is affected by the other. These interfered responses are described as follows;

$$E_t = A_t F_t + B_t F_n ,$$
  

$$E_n = A_n F_t + B_n F_n ,$$
(1)



- $E_t, E_n$ : response recorded on dynamometer (voltage).
- A, B: constant.



work piece (2) table to mount the work piece (3)(2) piezoelectric elements
 (5) insulating glass plate (6) synchroscope (7) steel base
 (a) Piezoelectric dynamometer



① dropping ball ③ triangular block ③ dynamometer(b) Calibration method

Fig. 1. Measurement of cutting force

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To calibrate the responce of the dynamometer by force, a dynamic method was used which was a dropped ball calibration method. A small ball was dropped onto the surface of the workpiece mounted on the dynamometer and the resulting signals were recorded. The relation between the impact force produced by dropping a ball and the pulse response was obtained as a problem of Hertzian contact and an impact problem. Their analysis is shown in another paper<sup>8</sup>. According to it, the maximum impact force  $P_m$  is obtained from the following equation whenever the Young's modulus of the dropped ball is smaller than that of the material being hit:

$$P_m = 3.35 \frac{m v_o}{\tau} , \qquad (2)$$

where m: mass of a ball,

 $v_o$ : velocity of impact of a ball,

 $\tau$  : duration of impact.

In the calibration test, if the Young's modurus of a ball is smaller the duration of impact is larger and it becomes easier to measure the impact force. Therefore, in this experiment, a soft rubber ball was used.

In single grit grinding, two components of the cutting force act on the dynamometer at the same time, as already mentioned. Then, in order to make the calibrating conditions close to the cutting conditions, some triangular blocks were used, as shown in Fig. 1(b). The ratio of the vertical to the horizontal component of the cutting force can be varied arbitrarily by changing the angle  $\theta$  of a triangular block. In the calibration test, the ball having a weight of 54 gr was dropped from a height of 1 m onto the surface of the workpice mounted on the dynamometer, and the duration of impact was measured. The impact force  $P_m$  was calculated by eq. (2) to be 42 kg ( $\tau=2$  m sec.).

Representing the responses of the vertical and the horizontal components of the cutting force on the dynamometer by  $S_t$ ,  $S_n$ , then eq. (1) becomes

$$S_{t} = A_{t}(P_{m} \sin \theta) + B_{t}(P_{m} \cos \theta),$$
  

$$S_{n} = A_{n}(P_{m} \sin \theta) + B_{n}(P_{m} \cos \theta),$$
(3)

where  $P_m$ : impact force,

 $\theta$ : angle of a triangular block.

Then, substituting 42 kg upon  $P_m$  and chainging the angle  $\theta$ , many trials of the ball droping test were carried out. Therefore many observation equations of the type of eq. (3) including the constant A and B were obtained, and it was determined by means of least squares method. As the results, two components of the cutting force were determined to be following equations:

$$F_t = 15.9S_t - 0.9S_n ,$$
  

$$F_n = 3.2S_t - 26.5S_n ,$$
(4)

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Reading the magnitude of the signals  $S_t$  and  $S_n$ , the responses of two components  $F_t$  and  $F_n$  are calculated.

#### 2.3 Measurement of extent of deformed zone

In order to detect the work hardened region beneath the groove formed by abrasive tool cutting, cross sections of the workpiece in vertical planes containing an axis X-X and planes perpendicular to it were obtained by cutting the workpiece with micro-cutter as shown in Fig. 2. Then the surface layer of the cross section was removed by degrees with chemical solution (HF 5%, H<sub>2</sub>O<sub>2</sub> 85%, H<sub>2</sub>O 10%) in order to remove the influence of cutting. In this way, the expected cross sections to be detected were obtained observing with micro-scope. The hardness on this cross section was measured with a micro Vikers hardness tester using a weight of 20 gr.



Fig. 2. Cutting directions of the work piece

#### 2.4 Compression test

D. Tabor<sup>4)</sup> has shown that the yield stress of a material is proportional to its hardness, and also B.R. Oliver<sup>5)</sup> showed that there was a reasonable agreement between the compression test data and the yield stress which was estimated from indentation hardness. Therefore, it is not so strange that the relation between the stress and strain coresponds to that between the strain and the hardness in compression tests, and this correspondence is also true for the strain behavior beneath the groove formed by abrasive grit cutting with a large negative rake angle. In order to obtain the deformed strain in the work material beneath the groove taking the results of Vikers hardness test into account, a compression test of the same material have been performed. The strain was calculated as the percentage reduction of length in compression test and the strain beneath the groove was estimated from that of the equivalent hardness in the compression test.

In the compression test attention was paid to make the test piece be compressed homogeneously. The surface roughness of the test piece finished was below 0.5  $\mu$  $R_{max}$ . Lubricating oil containing M<sub>0</sub>S<sub>2</sub> was used between the plate and the test



Fig. 3. Hardness in the test piece (Hv)

piece to remove friction on contact surfaces. It was confirmed that the test piece was compressed homogeneously and the hardness was almost the same everywhere within the specimen. Fig. 3 shows the hardness whithin the specimen.

In order to get the relation between stress and strain, the test piece was compressed gradually and every time when the load was removed the reduction of the test piece and the hardness of the material was measured. This operation was repeated and the result shown in Fig. 4 were obtained. Fig. 4(a), (b) show the relation between stress and strain and the relation between hardness and strain, respectively.

### 3. Experimental Results

#### 3.1 Cutting force

Cutting force varied during cutting operation as shown in Fig. 5. Therefore, in this experiment, an average cutting force was adopted. The average cutting force was denoted as an average response height, which is the height of the equivalent rectangular area under the response curve got through the dynamometer. Fig. 6 shows the horizontal component of the cutting force.



### 3.2 Deformed region in cutting

The contour lines of equal hardness of the deformed region beneath the groove which was formed by various cutting edges were obtained by hardness test. Fig. 7 is the result for a deformed region beneath the groove formed by the tool having an apex angle of 160°. Fig. 7(a) shows the contouor lines of equal hardness at the work surface; (b) and (c) are the ones at the cross section of the groove along (X-Z cross section) and perpendicular (Y-Z cross section) to the cutting direction re-



Fig. 6. Cutting forces (horizontal component)

spectively. The results obtained using another cutting edge with an apex angle of  $105^{\circ}$  are shown in Fig. 8 (a), (b) and (c). The number in the bracket shows the equivalent strain coresponding to the one obtained in compression test. From these results it is found that the deformed region is greater in its extent in cutting by







Fig. 7. Contour lines of equal hardness ( $\theta = 160^{\circ}$ )

(a) at the surface

(b) at the cross-section along the cutting direction (X-Z plane)

(c) at the crss-section perpendicular to the cutting direction (Y-Z plane)

larger apex angle edge. The deepest position of each contour line of equal hardness lies in the latter half of the groove length in Fig. 7 (b) and (c). On the other hand, the equal hardness lines by a sharp edge cutting tool given in Fig. 8 show the flat bottoms. These facts suggest that the material around the tool flows towards the direction of cutting and while some of it is removed as chips, some material is piled up as the swell out residual, and this tendency is significant in cutting by the tools having a large apex angle. It is found that there is a region where rubbing operation is dominant until the beginning of the metal removal operation in the cutting process with tools having a large negative rake angle, but this region becomes small in the case of sharp egde cutting tools. Therefore, in the case of cutting with large apex angle tools, the region without forming chips becomes large and the deformed region extends farther without forming chips, but in the case of shrp edge cutting tools the presence of flat bottom in the contour line of equal hardness is observed as shown in Fig. 8.

These tendencies become clear furthermore from a height coefficient obtained as a ratio of the average height of the swell out residual to the depth of cutting as shown in Fig. 9.

Observing the contour lines of equal hardness in the cross sections of workpieces, it is obvious that there is a difference between the extent of the deformed regions

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- Fig. 8. Contour lines of equal hardness ( $\theta = 105^{\circ}$ )
  - (a) at the surface
  - (b) at the cross section along the cutting direction (X-Z plane)
  - (c) at the cross section parpendicular to the cutting direction (Y-Z plane)



Fig. 9. Height coefficient along the cutting direction on the groove

caused by cutting with a large and a small apex angle tools .Representing the pattern of extent of the deformed region as a ratio of the maximum deformed distance to the maximum deformed breadth, it is found that the breadth of the deformed region extends more when it is cut with a larger apex angle tool as shown in Table 1.

T.O. Mulhearn<sup>6)</sup> studied the deformation of material by indentation tests with both conical and another type of indenters and reported that there are two types of mechanisms in deformation; one is the cutting mechanism in which the deformed zone should not extend to any considerable extent beneath the indenter, and this

θ°	105	125	135	160
Z <sub>max</sub> (mm)	0.29	0.36	0.41	0.49
Y <sub>max</sub> (mm)	0.20	0.29	0.32	0.55
$(Z_{max}/Y_{max})$	1.45	1.33	1.28	0.89

Table 1	1.	Extention	of	deformed	region
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Ymm

Fig. 10. Contour lines of equal hardness on the deformed region by indentation

mechanism is caused by a sharp indenter. The other is the compression type mechanism caused by the indenter with large apex angle, in which the deformation should extend for approxmately the same distance as that in a direction perpendicular to the indenter axis. In our experiment similar phenomena were observed.

Fig. 10 shows the contour lines of equal hardness beneath the indentation formed by a conical indenter with an apex angle of  $160^{\circ}$ . In this case the patern of contour lines is slightly different from the one obtained by cutting. The hardness lines are crossing the bottom of indentation, and the hardned region spreads more on the surface than in the direction of the indenter axis. These differences arise from whether the tool moves or not, which also results in a defference of the degree of material-flow and work-hardening.

#### 3.3 Deformation work absorbed by workpiece

To determine the deformation work absorbed by the work-piece during cutting, the relation between the hardness and the reduction of strain of the test piece in compression test was obtained. In compression test the work done by compression is represented as follows:

$$W = V \int_{l}^{l_o} \sigma_f \frac{dl}{l} \tag{5}$$

where V: volume of test piece,

 $l_o$ : length of test piece befor deformation,

*l* : length of test piece after deformation,

 $\sigma_f$ : flow stress of material,

The deformation work in compression test is seen to be consistent with the area under the stress-strain curve, and this is obtained from the experiments.

In the cutting experiment, the contour lines of equal hardness were obtained in three directions through hardness test on the cross sections of work-piece, and with these data the deformed region could be constructed three-dimensionally. This three dimensional deformed region was divided into many small blocks. The work absorbed in each block due to deformation was calculated corresponding to the results of compression test, and summing up the work absorbed in each block, the total deformation work beneath the groove was obtained.

### 3.4 Cutting work to form a groove

Cutting work to form a groove can be calculated from cutting force. The work done while the cutting tool progresses from a point P by a small distance  $\Delta x$  as shown in Fig. 11 is



Fig. 11. Explanation of tool movement

$$dW = F_n dz + F_i dx , (6)$$

Then the total work to form a groove is obtained by integrating it.

$$W = \int F_n dz + \int F_i dx , \qquad (7)$$

In the grinding, the vertical component of cutting force is usually about twice the horizontal component, but the depth of cut (d) is very small compared with cutting length. Hence, the term  $\int F_n dz$  in eq. (7) can be neglected in calculation. The total work to form a groove and also the deformation work beneath a groove were calculated, and the results are shown in Fig. 12 as a ratio between them.

According to the analysis<sup>7)</sup> of scraching by a conical tool, scraching force  $P_c$  is represented as follows

$$P_{c} = \left(\frac{2}{\pi} \cot \theta + \mu\right) P_{n}, \qquad (8)$$

where  $P_n$  is normal load

From this equation, the ratio of the frictional work  $(W_f)$  to the total work  $(W_i)$  needed to scrach is given by

$$\frac{W_f}{W_t} = \frac{\mu}{2/\pi \cot \theta + \mu} , \qquad (9)$$

where  $\mu$  is the frictional coefficient.

The values of eq. (9) are also represented in Fig. 12 with a parameter  $\mu$ . From these results it is found that the ratio of the frictional work to the total work increases with an increase in the apex angle of the cutting tool, and, similarly, the ratio of the deformation work to the total work needed to form a groove increases with the apex angle of the cutting edge, the ratio being 0.2–0.7, depending on the apex angle.



Fig. 12. The ratios of the deformation work  $(W_d)$  and the frictional work  $(W_f)$  to the total work  $(W_T)$ 

A. Kobayashi<sup>7</sup> reported that in scratching by a conical tool or a single grit, 60-70% of the cutting force was consumed as frictional force, and K. Sato<sup>8)</sup> also reported that the frictional work reached about 50-70% of the total work in the grinding operation. From these facts it is suggested that the most of the frictional work is consumed as the deformation work beneath the groove when it is cut with an abrasive grit or with tools having a large apex angle, and most of them might be transformed into heat.

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#### Conclusion

In general the deformed region beneath the groove extends greatly in cutting with abrasive tools and the deformation work may be considered to be pretty large. Therefore, the behavior of metal beneath the groove formed by modified abrasive tool cutting was investigated here and the following results were obtained:

(1) The deformed region beneath the groove extends as far as ten times the depth of cut and several times the breadth of cut respectively towords the direction of depth and breadth. Morover the pattern of extent of the deformed region depends on the apex angle of the cutting edge.

(2) Two mechanisms of deformation that T.O. Mulhearn mentioned in his indentation test, i.e. cutting mechanism and compression mechanism, were also observed in cutting. In the case of cutting with a sharp apex angle tool, the cutting phenomenon occurs easily but in cutting with a large apex angle tool, rubbing phenomenon is dominative.

(3) The swell out residual in the groove is significant in the latter half of the groove length. In the case of cutting with a large apex angle tool, this is due to the material flow during the cutting, and this phenomena corresponds to the pattern of the deformed zone beneath the groove.

(4) The ratio of the deformation work beneath the groove to the total work increases with an increase in the apex angle of the tool, and it it varies from 0.2 to 0.7 depending on the apex angle of the tool. This tendency is the same as that of the ratio of the frictional work to the total work to form a groove.

(5) The pattern of the deformed region by single grit cutting is defferent from that obtained by indentation test, especially at the bottom, and the deformation in the direction perpendicular to cutting Y-Y extends more than that in the case of indentation test.

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