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Observation of Cutting Mechanism of Cast Iron*

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The orthogonal cutting of cast iron was investigated in respect to the formation process of discontinuous chips.

Four types of discontinuous chip; shear type, tear type with a small crack, tear type with a large crack and crack type were recognized in the micro-photographs of chip formation process taken by a motor-driven 35 mm camera with a micro-flash illumination.

From enlarged profile of surface irregularity taken by a surface roughness meter under various cutting conditions, the number of cracks and the angle of cracked fracture to the cutting direction were measured.

As a result, it is understood that the type of chip produced depends on the cutting speed and the depth of cut, but not on the tool rake angle.

1. Introduction

Chips produced in metal cutting are divided into flow type, shear type, tear type and crack type. Though it is possible to observe the formation of flow type chips by the abrupt stopping method, it is impossible to investigate that of discontinuous chips by the same method because discontinuous chips are deformed after the abrupt stopping.

The purpose of this study is to investigate the formation process of discontinuous chips by micro-flashed photographs and enlarged profile of surface irregularity left on the finished work.

Plates of gray cast iron were cut orthogonally using a planing machine, while the polished side of the work was intermittently photographed during the cutting by a motor-driven 35 mm camera with a micro-flash illumination. The effects of cutting conditions on the chip formation process were investigated from a series of photographs. Then the profiles of irregularities and cracks on the surfaces machined under various cutting conditions were observed by a Talysurf roughness meter, and the relation between the cracked fractures and types of chip was investigated.

2. Equipment and procedure for the experiments

2.1 Experiment to take microphotographs by 35 mm camera with a micro-flash illumination

As shown in Fig. 1, the orthogonal cutting test

was conducted using a planing machine (table stroke 1000 mm, power 11 KW, maximum cutting speed 54 m/min). Olympus metal microscope (type NJ) was attached on the tool holder of the planer. Two micro-flash instruments used to illuminate the cutting point are characterized by a very short flash time, large flash power and proper concentration of light to a very small area. One of the lights illuminates the cutting point vertically through the prism contained in the microscope, and the other directly to produce cubic effects.

The workpiece was a plate (thickness 3 mm) of gray cast iron FC 20 (tensile strength 17 kg/mm²) machined from a bar as cast with 100 mm diameter. One side of the workpiece was polished. Chemical composition and hardness of the tested gray cast iron are shown in Table 1.

Table 1 Chemical composition and hardness of workpiece

Composi- tion	C	Si	Mn	P	S	Mo	Hardness H _v
FC 20	2.78	1.28	0.53	0.17	0.094	0.04	157

Fig. 1 Experimental equipment

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2.1.1 Experiments to take a series of pictures by a motor-driven 35 mm camera

Cutting processes were successively photographed by a motor-driven 35 mm camera with synchronized micro-flash illumination. The cutting conditions for this experiment were as follows; cutting speed: 5 mm/min, tool material: SKH-4 (10 % Co type), tool rake angle: 30 deg., tool relief angle: 8 deg., depth of cut: 0.3 mm, rate of photographing: 1 ~ 2

Fig. 2 The method to know the inclination angle from the surface irregularity

1-3
Workpiece: Gray cast iron, Cutting speed: 5 mm/min, Width of cut: 3 mm, Depth of cut: 0.3 mm, Tool rake angle: 30 deg, Tool relief angle: 8 deg, Tool material: SKH-4, Frame rate: 1 frame/sec

Fig. 3 Chip of shear type

frames/sec, flash time: 3 μ sec, flash power: 3 ~ 5 Wsec.

A very slow cutting speed of 5 mm/min was chosen to make it possible to observe the formation process of discontinuous chip successively by the motor-driven camera at a rate of 1 to 2 frames/sec. Tool rake angle as large as 30 degrees was selected to prevent the formation of side burr.

2.1.2 Experiment with a single frame photograph

In the practical range of cutting speeds, the aforementioned photographing method could not effectively follow the deformation speed of chip and work for successive photographing. Therefore, single picture method was used at those cutting speeds. As the flash time of this equipment was very short, the camera shutter was kept open. The cutting conditions for this experiment were as follows;

cutting speed: 2.5 5 10 20 40 m/min

tool material: HSS SKH-4 (10 % Co type)

tool rake angle: 30 deg., tool relief angle: 8 deg.

depth of cut: 0.3 mm, flash time: 1.7 ~ 3 μ sec

flash power: 3 to 5 Wsec

2.2 Measurement of the machined surface irregularity

To investigate the effect of cutting conditions on the profile of the surface irregularity, the profile of the surface irregularity was measured at the middle of the workpiece thickness for various cutting speeds, depths of cut and tool rake angles. The cutting conditions for this experiment were as follows;

cutting speed: 2.5 5 10 20 40 m/min (5 stages)

depth of cut: 0.05 0.1 0.2 mm (3 stages)

rake angle: 0 10 20 30 degree (4 stages)

tool material: HSS SKH-4, tool relief angle: 8 degree

The profile of surface irregularity was enlarged by magnification 20 in the cutting direction and magnification 200 in the vertical direction. Then the inclination angle θ of those cracked fractures which were deeper than 20 μ m was

calculated from the measured angle on the recording paper using the following equation.

$$\theta = \tan^{-1} \left(\frac{1}{10} \tan \theta' \right)$$

3. Test results and interpretation

3.1 Interpretation of photographs

Side views of orthogonally cutting process of cast iron are shown in the photographs of Fig. 3 to Fig. 6.

Figure 3 shows the shear type chip formation. The shear type chip was not observed frequently at extremely low cutting speeds, but its number increased with the cutting speed. Chips of the shear type are different from ones formed in cutting the low carbon steel at low speeds, and are characterized by fragmentary form. Inner texture of the fragmentary chips shows a slight deformation, whereas severe deformation is concentrated in a narrow band-like area. When this type of chip was produced, the machined surface was fairly smooth as the cracks propagated almost horizontally and did not

make deep hollows.

Figure 3, (1-1) to (1-3) are a series of pictures which show the formation of a shear type chip, and (2) to (4) are other three typical cases of shear type chip formation.

Figure 4 shows similar pictures for the formation of a tear type chip with a small crack. The crack which initiated around the tool edge in Fig. 4 (1-1) propagated along the graphite flakes as seen in (1-2). Propagation of this crack stopped at (1-2), leaving an increased clearance between chip and work. At the moment of picture (1-2), shearing deformation had started between the free surface and the tip of the crack. Then, the shear continued until the chip was separated perfectly as seen in Fig. 4 (1-3). Photographs (2) to (4) of Fig. 4 also indicate that shearing occurs between a free surface and the top of crack in producing the chips of this type. When a chip of this type is produced, the machined surface contains a steep but short fracture caused by the crack.

Figure 5 illustrates the formation of tear type

chip with a large crack. Initiation of a crack near the tool edge is seen in the picture (1-1), where the crack propagated, and also separated itself into two branches at the interval of a few pictures. One of the branches propagated to the free surface and separated the chip from the work by shearing. The other propagated forward further and became a large crack as seen in the picture (1-2). One frame after, the materials were torn at the root of chip to produce a large lump of chip. Figure 5 (2) shows the typical chip of tear type and typical tearing deformation between the free surface and the top of crack. Figure 5 (3) and (4) show the cracks which propagated along the flake of graphite in the cast iron.

This type of chip produces a long but shallow fractured surface on the finished work.

In Fig. 6, the crack type chip formation is demonstrated by a series of pictures from (1) to (6). A crack is formed along a graphite flake in front of the tool edge as shown in

(The experimental conditions are same as Fig. 3)
Fig. 4 Chip of tear type with a small crack

Fig. 6 (2), and it changes penetrating direction in a zigzag manner according to the directions of other graphite flakes as seen in the pictures (3) and (4). Finally, the crack reaches the free surface and then widens its clearance as seen in picture (5). Thus a large fragment of chip is separated from the work material as seen in Fig. 6 (6).

Those pictures typically show the progress of crack along the graphite flakes which leave an irregularly fractured surface.

However, since those pictures represent the side of the work-piece where the material undergoes free lateral deformation, the stress concentration at the ends of the graphite flakes must have been emphasized. Thus, it is questionable if the identical phenomena have occurred at the inside of the workpiece.

As a special case of crack type chip formation, it occurs that a crack propagates from the vicinity of tool edge upward and forward directly to the free surface. In this special case, the chip form is similar to that of shear type and no fracture of crack is left on the machined surface. It is also observed that the deformation of chip texture is restricted in

the narrower band than that which is observed in the chip formation of shear type. But it is difficult to distinguish this special type chip formation from the shear type, so far as the cutting of cast iron is concerned.

To facilitate comparison, the flow type chip formation in the cutting of brass (cutting speed 5 m/min), and the continuous chip formation with a built-up edge in the cutting of plain carbon steel S 45 C (cutting speed 30 m/min) are shown in the pictures of Fig. 7, as photographed by aforementioned method. Since present equipment can not effectively follow a high deformation speed, single shot picture method was used at higher cutting speeds. Figure 8 shows some of the pictures photographed at the cutting speeds from 2.5 to 40 m/min. Based on the observations made on all the photographs including those shown in Fig. 8, the following conclusions have been drawn;

(i) Under a certain cutting condition, and type of chip formation does not occur exclusively, but shear type, tear type and crack type chip formation are combined with certain proportions.

(ii) In the tested range of cutting speeds from 2.5 to 40 m/min the chip formation of crack type is less often observed.

(iii) Tear type is a typical chip formed at low cutting speeds, but rapidly decreases as cutting speed increases, and the tear type chip is scarcely found at 40 m/min speed.

(iv) The chips of shear type are found considerably at low cutting speeds, and they increase with the cutting speed. At the highest i.e., 40 m/min cutting speed tested, the shear type chip represents the majority of the chips.

3.2 The relation between the surface irregularity and the type of discontinuous chip

The four conclusions in the last section based on qualitative observations are to be supported by the numerical data taken from the finished surface. Because the aforementioned photographing was a tedious work and it produced fine pictures only when a tool of 30 degree rake angle was used in order to

(The experimental conditions are same as Fig. 3)
Fig. 5 Chip of tear type with a large crack

minimize side burrs, the aim was pursued by measuring the surface irregularity by the Talysurf roughness meter.

From the cutting mechanism and the observed chip type in the section 3.1, the following relations are assumed between the surface irregularity and

the type of chip.

(i) The shear type chip

When the chip of shear type is formed, the machined surface has no cracked fracture and therefore is smooth. Thus it is impossible to estimate the number of shear type chips directly from surface irregularity. However, it is possible to conclude that the shear type chips are predominantly formed when the discontinuous chips are produced together with a smooth machined surface.

(ii) The tear type chip

When the chips of tear type are formed, the machined surface contains long but shallow cracked fracture surfaces.

(iii) The crack type chip and a special case of tear type chip when there exist large graphite flakes having a large angle to the cutting direction, the cracks propagate along those graphite flakes. Thus the machined surface has deep and sharp cracked fractures.

Based on these assumptions it is possible to predict the type of chip from the knowledge on the surface irregularities such as the numbers and the angles of the cracked fracture existing on the machined surface. Therefore the numbers and the angles of cracked fractures which were deeper than $20\text{ }\mu\text{m}$, were observed by Talysurf roughness meter across a length of 60 mm over the surfaces

(The experimental conditions are same as Fig. 3)
Fig. 6 Chip of crack type

Workpiece: 4-6 brass, Cutting speed: 5 m/min, Width of cut: 3 mm, Depth of cut: 0.3 mm, Tool rake angle: 10 deg, Tool relief angle: 8 deg, Tool material: SKH-4

(a) Chip of flow type without a built-up edge

Workpiece: S45C steel, Cutting speed: 30 m/min, Width of cut: 3 mm, Depth of cut: 0.3 mm, Tool rake angle: 20 deg, Tool relief angle: 8 deg, Tool material: SKH-4

(b) Chip of flow type with a built-up edge

Fig. 7 Chip of flow type

Workpiece: Gray cast iron, Width of cut: 3 mm, Depth of cut: 0.3 mm, Tool rake angle: 30 deg, Tool relief angle: 8 deg, Tool material: SKH-4

Fig. 8 Chips at various cutting speeds

machined under various cutting conditions.

In Fig. 9, the numbers of cracks produced at various cutting speeds are shown in relation to their angles to the cutting directions. It is noted that the cracks whose angles are smaller than 25 degree are fewer at higher cutting speeds, but those larger than 30 degrees are unchanged with cutting speed. This means that the tear type chips which make shallower cracked fractures are principally formed at low cutting speeds and the number of shear type chips which do not make large cracked fracture increases as the cutting speed is raised.

In the same manner, Fig. 10 shows the number of cracks formed at various depths of cut versus the crack angles. It is noted that a greater depth of cut makes more cracks whose angles are less than 25 degrees. However the cracks deeper than 30 degrees are nearly constant in number irrespective of the depth of cut. This means that a greater depth of cut produces a greater number of tear type chips.

Considering above observation that the number of sharp angled fractures is unchanged regardless of cutting speed and depth of cut, and relating this to the photographs previously examined, it is understood that those surfaces are cracked fractures along graphite flakes. But this type of fractures is relatively less in number as seen in Fig. 9 and Fig. 10.

In this experiment, the tool rake angle did not influence the numbers and the angles of cracked fractures as shown in Fig. 11.

4. Conclusions

The orthogonal cutting of cast iron was investigated in connection with the formation processes of discontinuous chips at various cutting speeds, depths of cut and tool rake angles. From the photographs of cutting process and the profiles of surface

Sum of number of cracks produced at constant cutting speed, and various tool rake angles and various depths of cut (tool rake angle 4 stages $\times$ depth of cut 3 stages)

Fig. 9 Relation between the numbers of cracks and their angles to the cutting direction at various cutting speeds

Sum of number of cracks produced at constant depth of cut, and various cutting speeds and various tool rake angles (cutting speed 5 stages $\times$ tool rake angle 4 stages)

Fig. 10 Relation between the number of cracks and their angles to the cutting direction at various depths of cut

irregularity the following conclusions are drawn;

(1) Four types of discontinuous chip; shear type, tear type with a small crack, tear type with a large crack and crack type, are distinguished in the cutting of cast iron.

(2) The cracks propagate mainly along the graphite flakes in the cast iron.

(3) Tear type chips represent a majority of chips formed at lower cutting speeds, but its number rapidly decreases with higher cutting speed. On the contrary, the shear type chips are few among the chips produced at the lower cutting speeds, but it rapidly increases with higher cutting speed.

(4) A deeper cut produces a greater number of shear type chips.

(5) The cracked fractures which have large angles to the cutting direction, are considered to be made by the cracks propagating along the graphite flakes. The number of those cracks is fairly constant and is not affected by the cutting speed and the tool rake angles, and it remains relatively small.

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Sum of number of cracks produced at constant tool rake angle, and various cutting speeds and various depths of cut (cutting speed 5 stages $\times$ depth of cut 3 stages)

Fig. 11 Relation between the number of cracks and their angles to the cutting direction at various tool rake angles