single-blade coal planer, the resistance will be considered to be proportionate to the bit width (cutting height) h cm, because of the large bit width, and will be sought by the following formula⁽⁸⁾.

$$T \cong \frac{180ht^{0.5} \cdot 10^{0.35-0.01r}}{F_D^{0.9}} \text{ kg} \dots\dots\dots(11)$$

This report, however, does not elaborate on detail.

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On the Behavior of Chip in Steel Cutting*

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This paper describes the behavior of chip in steel cutting for the purpose of controlling the shape of chip and contains the following two parts. The first part describes the angle of flowing-out of chip and, since its values calculated by the theoretical equations are in accord with the measured values for various cutting conditions and tool designs, the authors have drawn up nomographs for the flowing-out angle of chip on the basis of the theoretical equations. The latter part describes the chip classification and the effect of cutting conditions on the shape of chip.

1. Introduction

Lately, with advancement in the quality of cutting tool material, a tendency to select high speed and high feed as cutting conditions is gradually gaining ground, which gives rise to a problem of chip control from the standpoint of safety of worker and the tool maintenance. The chip breaker is generally used for this purpose; however, its effective design cannot be worked out unless the behavior of chip produced by the tool without a chip breaker is known. Then, this paper discusses the direction of flowing-out and classification of chip in steel cutting.

2. Experimental procedure

The cutting was performed on a high speed lathe (Niigata Iron Works Co., swing 500 mm, center distance 1 100 mm, spindle speed 23~1 750 r.p.m., capacity of motor 15 H.P.). The material cut is carbon steel of 0.44%C, having the Rockwell hardness of B 89 and tensile strength of 64 kg/mm². The tool is of tungsten carbide S1 (Igetalloy grade), and its shape is shown in Fig. 1. It is finished by diamond wheel and diamond hand lapper.

3. The direction of flowing-out of chip

First of all, the direction of chip flowing out on the tool face is investigated. The angle θ between the flowing-out direction of chip and the center axis of the workpiece, which is shown in Fig. 1, is called "the angle of flowing-out" in the present paper. This angle is measured easily by observing with a universal measuring microscope the streak on the

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tool face caused by chip flow.

(i) **The effect of cutting velocity** This is shown in Fig. 2. From this figure it is evident that the angle of flowing-out is hardly affected by cutting velocity.

(ii) **The effect of the nose radius and depth of cut** This is shown in Fig. 3. The lines in the figure are drawn by using the theoretical equations referred to afterwards. The angle of flowing-out of chip increases with the nose radius of tool, and decreases with an increase of depth of cut. The latter effect is quite evident.

(iii) **The effect of feed** This is shown in Fig. 4. The lines in the figure are also drawn by using the theoretical equations referred to afterwards. It is evident from this figure that the effect of feed is not so remarkable and that the angle of flowing-out increases almost linearly with feed and the rate of increase is almost unaffected by depth of cut.

(iv) **The theoretical analysis of flowing-out angle of chip** In order to obtain theoretically the angle of flowing-out of chip, the following is assumed: concerning an arbitrary small portion of the cutting edge, it is assumed that the chip of that portion flows out at right angles to the edge because of approximate orthogonal cutting for the small portion. The flowing-out angle of entire chip is considered as an average of the flowing-out angles on the small portions over the entire cutting edge, which is expressed as follows:

$$\theta = \frac{\int \theta_x d\chi}{\int d\chi}$$

where $d\chi$ is the small length of the cutting edge where cutting is performed and θ_x is the flowing-out angle on that portion. Although the above expression is introduced under the assumption that the cutting resistance acting on the small portions is uniform over the entire cutting edge—which results in neglecting the change of chip thickness of each portion along the cutting edge—the authors have tentatively calculated the flowing-out angle for various conditions by this expression. At first, the six cases must be considered, as shown in Fig. 5, from mutual relations between the three factors: nose radius r , depth of cut t and feed s . β is the end cutting edge angle.

1a) $s \leq 2r \sin \beta$, $t \geq r$: The cutting edge participating in actual cutting is divided into two parts: $\overline{AB}$ and $\widehat{BC}$. Each length and flowing-out angle of chip produced from each part are as follows:

	Length of cutting edge	Flowing-out angle
$\overline{AB}$	$t - r$	0
$\widehat{BC}$	$r \left(\frac{\pi}{2} + \sin^{-1} \frac{s}{2r} \right)$	$45 + \frac{1}{2} \cdot \frac{180}{\pi} \sin^{-1} \frac{s}{2r}$

Fig. 1

Nose radius 1.5 mm, Feed 0.3 mm/rev

Fig. 2

Cutting velocity 150 m/min, Feed 0.3 mm/rev

Fig. 3

Hence,

$$\theta = \frac{\left(\frac{\pi}{2} + \sin^{-1} \frac{s}{2r}\right) \left(45 + \frac{90}{\pi} \sin^{-1} \frac{s}{2r}\right)}{\left(\frac{t}{r} - 1\right) + \left(\frac{\pi}{2} + \sin^{-1} \frac{s}{2r}\right)} \dots (1)$$

Then, the following equation are obtained by the same procedure.

1b) $s \leq 2r \sin \beta$, $t < r$:

$$\theta = 90 - \frac{90}{\pi} \left\{ \cos^{-1} \left(1 - \frac{t}{r}\right) - \sin^{-1} \frac{s}{2r} \right\} \dots (2)$$

2a) $r \left(1 + \frac{1}{\sin \beta}\right) \geq s > 2r \sin \beta$, $t \geq r$:

$$\theta = \frac{\left(\frac{\pi}{2} + \frac{\pi}{180} \beta\right) \left(45 + \frac{\beta}{2}\right) + \left\{ \frac{s}{r} \cos \beta - \sqrt{\frac{2s}{r} \sin \beta - \left(\frac{s}{r}\right)^2 \sin^2 \beta} \right\} (90 + \beta)}{\left(\frac{t}{r} - 1\right) + \left(\frac{\pi}{2} + \frac{\pi}{180} \beta\right) + \left\{ \frac{s}{r} \cos \beta - \sqrt{\frac{2s}{r} \sin \beta - \left(\frac{s}{r}\right)^2 \sin^2 \beta} \right\}} \dots (3)$$

2b) $r \left(1 + \frac{1}{\sin \beta}\right) \geq s > 2r \sin \beta$, $t < r$:

$$\theta = \frac{\left\{ \cos^{-1} \left(1 - \frac{t}{r}\right) + \frac{\pi}{180} \beta \right\} \left\{ 90 - \frac{90}{\pi} \cos^{-1} \left(1 - \frac{t}{r}\right) + \frac{\beta}{2} \right\} + \left\{ \frac{s}{r} \cos \beta - \sqrt{\frac{2s}{r} \sin \beta - \left(\frac{s}{r}\right)^2 \sin^2 \beta} \right\} (90 + \beta)}{\left\{ \cos^{-1} \left(1 - \frac{t}{r}\right) + \frac{\pi}{180} \beta \right\} + \left\{ \frac{s}{r} \cos \beta - \sqrt{\frac{2s}{r} \sin \beta - \left(\frac{s}{r}\right)^2 \sin^2 \beta} \right\}} \dots (4)$$

3) $s > r \left(1 + \frac{1}{\sin \beta}\right)$, $t > s \tan \beta - \frac{r}{\cos \beta}$:

$$\theta = \frac{\left(\frac{\pi}{2} + \frac{\pi}{180} \beta\right) \left(45 + \frac{\beta}{2}\right) + \frac{\frac{s}{r} - (1 + \sin \beta)}{\cos \beta} \cdot (90 + \beta)}{\left(\frac{t}{r} - 1\right) + \left(\frac{\pi}{2} + \frac{\pi}{180} \beta\right) + \frac{\frac{s}{r} - (1 + \sin \beta)}{\cos \beta}} \dots (5)$$

4) $r = 0$:

$$\theta = \frac{\frac{s}{\cos \beta} \cdot (90 + \beta)}{t + \frac{s}{\cos \beta}} \dots (6)$$

The values calculated from Eqs. (1) to (6) are shown with lines in Figs. 3 and 4. They coincide fairly well with the experimental results, especially those for small depth of cut and small nose radius,

Cutting velocity 150 m/min, Nose radius 1.0 mm

Fig. 4

Fig. 5

in spite of rough assumption made in the induction of the theoretical equation. In order to know such flowing-out angle of chip easily, its graphical representation obtained from the above theoretical equations is shown in Figs. 6 and 7. Fig. 6 shows six classifications (Fig. 5) depending upon the end cutting edge angle β , nose radius r , feed s and depth of cut t . For $\beta=5$ deg., for example, the ranges divided with oblique lines show these classifications. Thus, by having this classification in mind, the angle of flowing-out of chip can be calculated from the theoretical equations obtained from the graphical representation indicated in Fig. 7, which shows the relations among feed s , depth of cut t , nose radius r and flowing-out angle θ for $\beta=5$ deg.

4. Shapes of chip

(i) **Chip classification** Fig. 8 shows the chip classification. Extremely high speed cutting of steel produces the straight type of chip indicated as the type I, which is either straight or curled with a very large radius. The curl radius of chip decreases gradually with a decrease of cutting velocity, but shows a tendency to increase sometimes. For this reason, a continuous and irregular helical

chip is produced, which is indicated as the type II. With a lesser cutting velocity, the flat helices type of chip with equal curl radius, indicated as the type III, is produced. This is, so to speak, the fundamental shape of chip. With a lesser depth of cut, equality of curl radius of chip is disturbed and the type IV chip appears, and then the type V chip of disordered block is produced. Taken altogether, when the continuous type of chip is produced in steel cutting and if there is no external force acting on the chip, one of these five types of chip is formed. However, the shape of chip changes when an external force acts on it; that is, the chip is bent by the chip breaker or run against the shank. In this case, the broken-off types of chip as shown in the lower part of Fig. 8 are produced.

(ii) **The effect of depth of cut and cutting velocity** This is shown in Fig. 9. The cutting velocity within the range used in this experiment hardly affects on the shape of chip. With an increase of cutting velocity, however, the type III chip is not easily formed, and the chip produced tends to be similar to the type I in the case of a larger depth of cut and to the type II or IV in the case of a smaller depth of cut. With an increase of depth of cut, the chip generally shifts as follows:

Fig. 6

Fig. 7

the type IV → the type III → the type II → the type I.

(iii) **The effect of feed** This is shown in Fig. 10. Above 1.5 mm of depth of cut and 0.65 mm/rev of feed, the broken-off type of one turn is produced. Even at such a large depth of cut, with a decrease of feed below 0.5 mm/rev, the chip tends to be of the type III through the type III'_a and then the type II. Below 1 mm of depth of cut, the chip is of the type IV in the case of a small feed, and the type II in the case of a large feed.

(iv) **The effect of the nose radius** This is shown in Fig. 11. In the case of a large nose radius, the type II chip is generally produced. But in the case of a large depth of cut, the chip tends to be of the type III with a decrease of the nose radius. With a decrease of depth of cut, the chip has a tendency to be of the broken-off type, i.e. the type III'_a or III'_b. Such a tendency is strongest at the depth of cut of about 1 mm. With a lesser depth of cut, the chip is not easily broken off, and at the depth of cut of 0.25 mm the chip produced is of the type IV.

(v) **Discussion** The shape of chip depends on the state of chip curl. In the case of a three-dimensional cutting, two states of chip curl can be considered: the state of chip curl having its axis parallel to the cutting edge [Fig. 12(a)], and the state of chip curl with its axis perpendicular to the cutting edge [Fig. 12(b)]. The former produces the cylindrical helices type of chip with a brilliant external surface. The former type has hardly been formed in the above experiment, but the latter has appeared almost always. At this time the chip produced is the flat helices type.

As mentioned before, the shape of chip changes depending upon cutting conditions and the reason for it, it is considered, lies in the degree of state of chip curl. This is shown in Figs. 13, 14, and 15, where the effects of cutting velocity, feed and depth of cut on radius of chip curl are indicated. For extremely small depth of cut or feed, the V or IV chip is always produced, while for great chip-thickness the phenomenon of breaking-off of chip occurs. Such phenomenon is considered as follows: the chip which has flowed out of the cutting edge is curled on the horizontal plane and contacts with the side of tool or the workpiece. For this reason the chip is bent upwards. If the stress produced in the chip by such deformation is under the breaking limit of the material, the chip will be continuous, and if the stress is over the breaking limit, the chip will be broken off. And if the stress is nearly equal to the breaking limit, the chip will be broken off with several turns. In this case,

since the strain (i.e. deformation) is identical, the larger the sectional area of chip the easier the breaking-off of chip. It is considered, therefore, that the large feed and the small ratio between

the nose radius and depth of cut are effective for chip to break off.

5. Conclusions

The above experiment and discussion lead to the following conclusions on the behavior of chip in steel cutting.

a. The direction of flowing-out of chip

(1) The cutting velocity within a range of 50~220 m/min hardly gives any effect on the direction.

(2) With an increase of the nose radius or with a decrease of depth of cut, the direction goes away from the workpiece.

(3) The effect of feed is small in comparison with other factors, however, with an increase of feed the direction tends to go away from the workpiece.

(4) The theoretical equations for the angle

of flowing-out of chip is in a fairly good agreement with the experimental results and the nomographs for the angle of flowing-out of chip can be drawn by using them.

b. The shape of chip

(1) The chip classifications of five continuous types and five broken-off types are presented.

(2) With an increase of cutting velocity and depth of cut, the curl radius of chip increases and the straight type of chip is produced.

(3) With an increase of feed, the curl radius also increases, but an excessive increase of feed over certain limit produces the broken-off type of chip.

(4) With an increase of the nose radius, the curl radius usually increases, and with its decrease the chip tends to be of the broken-off type except in the case of excessively small or large depth of cut.

Fig. 12

Fig. 13

Fig. 14

Fig. 15