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A Study on Chip-breaker*

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Limiting condition of chip breaking with a parallel type chip-breaker has been found to be determined by only the following three items: the radius of chip flow circle, the material to be cut and the thickness of chip.

The larger the radius of chip flow circle, the steeper the slant of a chip-breaker and the thinner the chip, the smaller was the force acting on a chip-breaker due to chip curling. The yield stress of chip was found to become about twice that of the same material before cut.

From these results, a simple method for finding the optimum shape of a chip-breaker was established. In this method, a proper radius of chip flow circle is found directly by measuring the thickness of chip which is obtained under the given cutting conditions and by the use of a diagram presented in this paper.

1. Introduction

Modern high-powered machine tools with cutting tools of sintered carbide have increased the rate of chip formation, and it has become a serious problem to use the efficient chip-breaker which makes the chip properly broken for convenient handling and disposal. For the design of an efficient chip-breaker, E. K. Henriksen arranged his numerous experimental results into diagrams through the introduction of the modified feed and the radius of chip flow circle⁽¹⁾.

In this report, the chip breaking by a chip-breaker was analysed, and a simple method for finding the limiting conditions of chip breaking was found. The force acting on the chip-breaker was also studied analytically and experimentally. As the results, it has become very easy to design the optimum shape of a chip-breaker.

2. Limiting conditions of chip breaking

2.1 Breaking of chip with a chip-breaker

There are three types of chip breaking with a chip-breaker which are shown in Fig. 1⁽²⁾. In most cases, however, chips are broken up through Type C in the figure, though it has the defect to abrade the flank of the cutting tool. Therefore, only Type C breaking is considered here.

The limiting conditions of the Type C breaking seem to be determined as follows: A chip which was born with a radius of curvature R_0 (Fig. 2(a))

Fig. 1 Three types of chip breaking with chip-breaker

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will be broken up if the strain of its skin reaches the maximum elongation of the chip material before the point of the chip can escape through the bottom of the tool. This condition will be

$$\varepsilon < \frac{t_2}{2} \left(\frac{1}{R_0} - \frac{1}{R_L} \right) \quad (1)$$

where ε is the strain at which the chip material is ruptured, t_2 is the chip thickness, R_L is the maximum radius of curvature when the point of chip reaches the bottom of the tool shank (Fig. 2 (c)).

Then the factors which determine the chip breaking directly are only four items, ε , t_2 , R_0 and R_L , which are included in Eq. (1). ε will be determined mainly by the material to be cut. t_2 will be varied by cutting conditions such as feed, cutting speed, rake angle, side cutting edge angle, etc. R_0 will have intimate relation with the radius of chip flow circle of the chip-breaker. As the chip is considered as a curved beam fixed at one end and loaded at three points, namely, at the chip-breaker, the workpiece and the tool flank, R_L is hard to be presumed. The height of tool shank will have most intimate relation to R_L . R_L will have, however, less effect on the chip breaking than R_0 has, because R_L is fairly larger than R_0 .

2.2 Experiments on the limiting condition of chip breaking

2.2.1 Experimental procedure In relation with the above consideration, the following tests were performed using the Shoun-Cazeneuve HB 500 lathe equipped with a 12 HP main motor. Cutting tools used were grade S-2 sintered carbide with the geometry of 0-0-7-7-8-0-0.5 mm inserted into the clamp type holder. Parallel type chip-breakers with the

Fig. 2 Limiting condition of type C chip breaking

Fig. 3 Radius of chip flow circle R_c

slant θ (Fig. 3) of 45 deg. were clamped on the rake face. By adjusting the width b in Fig. 3, the radii of chip flow circle R_c were determined in accordance with the following relation:

$$R_c = b \cot(\theta/2) \quad (2)$$

The tests were run on the steel bars from 90 to 60 mm in diameter and 500 mm long. In the greater part of the tests, S 45 C steel (0.45 % C) was used as received. S 15 C steel (0.15 % C), S 55 C steel (0.55 % C), SCM 3 steel (Cr-Mo steel) and SUS 7 steel (18-8 stainless steel) were used for the purpose of comparison. The thickness of chip was measured by the micrometer which has the spindle with a rounded point.

2.2.2 Effects of feed and cutting speed Feed and cutting speed varied the limiting condition of chip breaking as is shown in Fig. 4. In general, the lowest feed for chip breaking increases with the increase of cutting speed. The deviation from this

Fig. 4 Effects of feed and cutting speed on chip-breaking

Conditions are same as in Fig. 4

Fig. 5 Effects of chip thickness and cutting speed on chip breaking

trend at the lowest cutting speed is due to the presence of a built-up edge.

Fig. 5 shows the effect of cutting speed and chip thickness in the same experiment. It can be seen in the figure that the limiting chip thickness for chip breaking does not vary with the cutting speed when there is no built-up edge. This fact tells us that the cutting speed has no direct effect on the chip breaking, and that the increase of cutting speed increases the limiting feed for chip breaking only because it decreases the chip thickness. Accordingly, when we notice the chip thickness instead of feed, we can neglect the effect of cutting speed. Other effects of cutting speed on chip breaking such as the work-hardening and the temperature-rise of chip were not found in this experiment.

2.2.3 Effect of rake angle The effect of rake angle on the limiting condition is shown in Fig. 6 where the rake angle was varied by the tapered shims. The limiting chip thickness seems to be practically constant for usual rake angle (from +12 deg. to -7 deg.), though it increases for an extremely large negative rake angle.

2.2.4 Effect of side cutting edge angle The increase in the side cutting edge angle decreases the undeformed chip thickness, $t_1 \cos \varphi$ in Fig. 7, and, accordingly, decreases the chip thickness. Then, according to Eq. (1), the chip will become hard to be broken up.

Material: S45C, Depth of cut: 2.0 mm, R_c : 4.1 mm
Fig. 6 Effect of rake angle on chip breaking

Fig. 7 Relation between side cutting edge angle and undeformed chip thickness

When the side cutting edge angle was varied by revolving the tool post, the limiting condition for chip breaking was varied as is shown in Fig. 8. Though the limiting feed is increased with the increase of φ , $(\text{limiting feed}) \times \cos \varphi$ and the limiting chip thickness do not vary as expected from Eq. (1). Then the use of chip thickness as the limiting condition of chip breaking will also exclude the effect of side cutting edge angle.

If the side cutting edge angle is increased to 45 deg., however, the chip becomes a coil with large pitch, not contacting with the workpiece and, then, not being pushed down so as to collide with the flank of tool.

2.2.5 Effect of depth of cut In general, the depth of cut does not change the thickness of chip, and then, according to Eq. (1), will have no effect on chip breaking. Fig. 9 shows that the limiting

Material: S45C, Cutting speed: 130 m/min, Depth of cut: 2.0 mm, R_c : 4.6 mm

Fig. 8 Effect of side cutting edge angle on chip breaking

Material: S45C, Cutting speed: 130 m/min
Fig. 9 Effect of depth of cut on chip breaking

condition for chip breaking is actually not varied when the depth of cut is larger than 2.0 mm.

When the depth of cut is decreased to smaller than 2.0 mm, however, the limiting chip thickness decreases in the beginning, and then increases steeply. This change seems to be due to the two opposite effects of the change in the direction of chip flow. The angle between the side cutting edge and the direction of chip flow decreases with the decrease of depth of cut. The decrease of this angle makes the chip easy to contact with the workpiece and to be broken up, but, on the contrary, increases the actual radius of chip flow circle and makes the chip hard to be broken up.

2.2.6 Effects of the sizes of tool shank and workpiece The increase in the height of tool shank seems to increase the radius R_L in Eq. (1) and to make the chip easy to break up. The use of an obstacle plate (Fig. 10) which corresponds to the triplication of the height of shank, however, produced no change in the limiting condition of chip breaking. This will be due to the fact $R_L \gg R_0$ as was explained in 2.1.

The decrease in the diameter of the workpiece from 90 mm to 30 mm also produced no change in the limiting condition.

2.2.7 Effects of the radius of chip flow circle

Fig. 10 Obstacle plate for chip breaking

Material: S 45 C, Cutting speed: 110 m/min, Depth of cut: 2.0 mm, x: broken chip, o: continuous chip

Fig. 11 Effects of radius of chip flow circle and feed on chip breaking

R_0 and the material to be cut. The increase in R_0 increases the radius of curvature R_0 , and, in accordance with Eq. (1), will increase the feed for chip breaking. In fact, the feed for chip breaking in the turning of S 45 C steel increased with the increase in R_0 as is shown in Fig. 11.

Similar experiments were made on the other steels, S 15 C, S 55 C, SCM 3 and SUS 7. The limiting feeds for chip breaking obtained are plotted in Fig. 12 together with that on S 45 C. The relations between the limiting chip thickness for chip breaking and R_0 obtained are shown in Fig. 13. It can be seen in Fig. 13 that the curves approach each other, and the curves for three carbon steels practically fall into one. Accordingly, it can be said that the differences in the carbon content of the carbon steels do not change the ductility of those steels when they are severely deformed into chip. High carbon steel produces a thinner chip than low carbon steel does, and, as the result, the former needs larger feed for chip breaking than the latter does, as is seen in Fig. 12. It can also be observed in Fig. 13 that, when deformed into chip, SCM 3 is more ductile and SUS 7 is less ductile than carbon steels are.

2.3 A consideration on the radius of chip flow circle

Radius of chip flow circle R_c mm

Cutting speed: 110~120 m/min (150 m/min for S15C), Depth of cut: 2.0 mm

Fig. 12 Relation between radius of chip flow circle and the limiting feed for chip breaking

Radius of chip flow circle R_c mm
Conditions are same as in Fig. 12

Fig. 13 Relation between radius of chip flow circle and the limiting chip thickness for chip breaking

In the above experiments, the radius of chip flow circle R_c was used as a substitute for the radius of curvature of chip R_0 which was considered in Eq. (1) as the determinant of chip breaking. Though R_c is not equal to R_0 , the limiting conditions were practically determined by R_c very well. The reason for this fact seems to be as follows:

In order to bring R_c close to R_0 , $(b-m)$ should be used instead of b in Eq. (2), as was pointed out by T. Sata, where m is the length of tool-chip contact (Fig. 14); m was found in the author's experiments⁽³⁾ to have the following relation in the wide range of cutting conditions:

$$m = k_m t_1 \{ \sin(\phi + \beta - \alpha) / \sin \phi \cos \beta \} \dots\dots\dots (3)$$

$$= k_m t_2 \left\{ \frac{2 \sin \omega}{\cos \omega + \cos(\omega - 2\beta)} \right\} \dots\dots\dots (4)$$

where, k_m is a constant (about 2.0), t_1 is the thickness of cut, t_2 is the thickness of chip, ϕ is the shear angle, β is the friction angle between tool face and chip, and ω is the angle between the direction of the resultant cutting force and the shear plane; ω was also found to be determined by only the material to be cut and slightly varied by the rake angle α . In the usual cutting condition, the variation in β is not extensive. Accordingly, for a given material to be cut, m can be considered to be approximately proportional to t_2 and be independent of other factors.

Fig. 14 Cutting geometry

Fig. 15 Effect of radius of chip flow circle on cutting force, thrust force and chip thickness

The other reason for the difference between R_c and R_0 is due to the elastic deformation of the chip due to the bending moment imposed by the chip-breaker. K. Okushima, T. Hoshi and T. Fujinawa⁽⁴⁾ studied on this problem and revealed that R_0 is determined by the following three items: the shape of chip-breaker, the material to be cut and the thickness of chip.

It is very troublesome and not practical to get R_0 for each cutting by applying the two theories. But these two theories showed that R_0 is substantially determined by the material to be cut, chip thickness t_2 and the radius of chip flow circle R_c . Namely,

$$R_0 = f_1 (\text{material to be cut}, t_2, R_c) \dots\dots\dots (5)$$

On the other hand, from Eq. (1),

$$\text{Limiting chip thickness} = f_2$$

$$(\text{material to be cut}, R_0) \dots\dots\dots (6)$$

Then, Eqs. (5) and (6) show the presence of the following relation:

$$\text{Limiting chip thickness} = f_3$$

$$(\text{material to be cut}, R_c) \dots\dots\dots (7)$$

Fig. 13 seems to be the real form of this equation.

2.4 The effects of the radius of chip flow circle other than the chip breaking

An experimental result, Fig. 15, shows the variations of cutting force, thrust force and chip thickness due to the variation of R_c . The force acting on the chip-breaker is included in the two forces. Though the chip was broken up for $R_c < 7$ mm, it can be seen in this figure that proper choice of R_c (3~5 mm in this case) decreased the two forces and chip thickness. This fact tells us that the chip-breaker with proper R_c lifts up the chip, decreases the length of tool-chip contact and, as the result, decreases the tool-chip friction. These decreases in the forces contribute not so much to the saving of cutting power, but they shall decrease the tool wear.

Excessively small R_c , however, obstructs the chip flow and increases the forces and chip thickness as can be seen in the left ends of the curves in Fig. 15.

3. Force acting on chip-breaker

3.1 Consideration

To avoid the wear and damage, it is necessary for the chip-breaker to have such a shape as to minimize the force which acts upon it. Two forces acting upon the chip-breaker are the force to curl the chip at its root, A in Fig. 16, and the force to break up the chip. The latter is intermittent and is smaller than the former because the greater part of the force for chip breaking is in charge of the workpiece and the tool flank. Accordingly, only the force to curl the chip is considered here.

In Fig. 16, the bending moment at the root of chip A due to the force acting on a chip-breaker is

$$M_A = P \cdot \overline{AC} = P \cdot R_c \{ \sin(\theta + \beta) - \sin \beta \} \quad \dots\dots (8)$$

$$\beta = \tan^{-1} \mu = 90 \text{ deg.} - \theta - \tan^{-1}(P_V/P_H) \quad \dots\dots (9)$$

where, μ is the friction coefficient between chip and chip-breaker, and the other notations are as shown in Fig. 16. The stress distribution in the chip at A will be such as is indicated in Fig. 17 by a solid line. But, if it is simplified into a rectangular shape (dotted line in Fig. 17), M_A must be

$$M_A = w t_2^2 \sigma_A / 4 \quad \dots\dots\dots (10)$$

where, w is the width of chip, t_2 is the chip thickness and σ_A is the yield stress of the chip. From Eqs. (8) and (10), the following relation is obtained:

$$P = \frac{w t_2^2 \sigma_A}{4 R_c \{ \sin(\theta + \beta) - \sin \beta \}} \quad \dots\dots\dots (11)$$

3.2 Experiments

3.2.1 Experimental procedure In relation with the above consideration, the following experiments were performed. A tubular workpiece was cut

Fig. 16 Force acting on chip-breaker

Fig. 17 Stress distribution in chip

Fig. 18 Measurement of the force acting on chip-breaker

orthogonally with a specially designed cutting tool which is shown in Fig. 18. Adjacent to, but separated from the tool, a chip-breaker was installed on a tool-dynamometer which recorded the two components of the force acting on the chip-breaker. The material of the workpiece was a mild steel. The tubular workpiece with 137 mm outside diameter and 2.0 mm wall thickness took the coiling chip into itself and did not break up. Therefore, only the forces for the chip bending considered above were measured. The cutting tool used was S-2 grade sintered carbide with 0 deg. rake angle and 7 deg. relief angle. The chip-breaker was a hardened and ground carbon tool steel.

Besides the horizontal and vertical components, P_H and P_V , of P , the chip thickness t_2 was measured. Using these values, M_A can be obtained from Eqs. (8) and (9), and σ_A can be obtained from Eq. (10).

3.2.2 Effect of the radius of chip flow circle R_c Fig. 19 was obtained by varying the width of chip-breaker b and keeping the slant θ to 60 deg. With the increase in R_c , P decreases as is expected from Eq. (11). But the increase in t_2 and the decrease in σ_A can also be seen in the figure.

3.2.3 Effect of the slant of chip-breaker θ In Fig. 20, keeping R_c constant, the slant of chip-breaker θ was varied. The increase in θ decreases P as was shown in Eq. (11). In this case, the variations of t_2 and σ_A are not remarkable.

3.2.4 Effect of feed Fig. 21 shows the effect of feed when R_c and θ are kept constant. P increases with the increases in feed and, accordingly,

Radius of chip flow circle R_c mm
Cutting speed : 98 m/min, Feed : 0.1 mm/rev,
Slant : 60 deg.

Fig. 19 Effect of radius of chip flow circle

in chip thickness t_2 . Fig. 23, in which the relations between P and t_2 are plotted, shows, however, that P is proportional not to t_2^2 , as was predicted in Eq. (11), but to t_2^4 . This will be the result of the increase in σ_A with the increase in feed, which is seen in Fig. 21.

3.2.5 Effect of cutting speed The increase

Cutting speed : 98 m/min, R_c : 6.0 mm,
Feed : 0.15 mm/rev

Fig. 20 Effect of slant of chip-breaker

Cutting speed : 98 m/min, R_c : 6.0 mm,
Slant : 60 deg.

Fig. 21 Effect of feed

in cutting speed decreases P as can be seen in Fig. 22. This seems to be due to the decrease in the chip thickness t_2 with the increased cutting speed. Fig. 23 shows, however, that P is proportional not to t_2^2 but to t_2 . This fact can also be explained by the increase in σ_A with the increased cutting speed, which can be seen in Fig. 22.

3.3 Relation between σ_A and shear strain

Above experiments showed that the increases in R_c and θ and the decrease in t_2 decreased P , and that the simplified consideration in 3.1 was reasonable qualitatively. They showed, however, that the variation of σ_A contributed to the variation of P . Namely, the increase in R_c and the decrease in feed and cutting speed increased σ_A and, accordingly, P . These variations of σ_A can be explained by the temperature-rise of chip due to the deformation at the chip formation. The increase in R_c and the decrease in feed and cutting speed decrease the cut-

Cutting speed : 0.1 mm/rev, R_c : 6.0 mm, Slant : 60 deg.

Fig. 22 Effect of cutting speed

Fig. 23 Relation between chip thickness and P

Table 1 Tension test of chip

No.	1	2	3	4	5	6	7
Rake angle deg		45	35	27	10	10	10
Feed mm/rev	Before cut	0.30	0.30	0.20	0.20	0.20	0.20
Cutting speed m/min		50	50	168	168	168	76
Cutting liquid		Soluble oil	None	None	Soluble oil	None	None
Shear strain	0	1.1	1.7	2.1	2.9	3.1	4.0
Tensile strength kg/mm ²	46	75	84	91	92	93	95

ting ratio, increase the shear strain and, as the result, raise the temperature at the shear plane. In the steel cutting under usual cutting condition such as in the above experiments, the temperature at the shear plane is between 300 and 600 deg. C. The yield stress of steel at such a range of temperature is varied with temperature very sensitively.

The relations between σ_A and the shear strain of the chip obtained in the above experiments, i.e., Figs. 19, 21 and 22, are plotted in Fig. 24. It can be seen that σ_A decreases with the increase of shear strain as was supposed above.

3.4 Tension test of chip

The yield stress σ_A in the above experiments often reached about 100 kg/mm², which seemed to be too large for a mild steel. There also is a doubt why the increase in the strain-hardening due to the increase in the shear strain did not cancel the decrease in σ_A due to the temperature-rise.

Tension tests were performed to get the knowledge about the tensile strength of chips with various shear strains. Test pieces were obtained from the mild steel used in the above experiments and the chips produced in the cutting of the same material under various conditions which are shown in Table 1. These test pieces were finished to have a parallel section of 15 mm long, 1.5~1.9 mm in width and 0.2~0.5 mm in thickness. Using wood metal, the both ends of the test pieces were fixed into holders. Tensile strength was measured by an apparatus equipped with a spring balance.

For each kind of chip, two test pieces with different sizes of cross section were tested, and the tensile strengths obtained from these two always agreed with each other within an error of 2%. The mean values from these two test pieces are shown in Table 1 and Fig. 25.

These results show that the tensile strength of chip reaches such a large value as twice that of the same material before cut; 100 kg/mm² which was obtained in the previous experiments as the value of σ_A seems to be reasonable. Fig. 25 also shows that, as far as the strain of chip is larger than 2, which is common in the usual cutting con-

Fig. 24 Relation between the shear strain of chip and σ_A

Fig. 25 Relation between the shear strain and the tensile strength of chip

dition, the increase in the shear strain of chip does not change the tensile strength. The strain hardening is saturated at these large strains.

These results can, therefore, justify the experimental relation in 3.3.

4. Conclusions

Following conclusions were obtained from the above study:

- (1) Under the usual cutting condition, the

limiting condition for the chip breaking by a chip-breaker is determined only by three items: the radius of chip flow circle, the material to be cut and the chip thickness.

(2) Feed, cutting speed and side cutting edge angle affect the limiting condition only through the variation in the chip thickness.

(3) The limiting condition for chip breaking is usually not varied with the factors which do not change the chip thickness such as the depth of cut and the sizes of tool shank and workpiece.

(4) The increase in the radius of chip flow circle increases the limiting chip thickness for chip breaking almost linearly.

(5) The carbon content in carbon steel have no effect on the limiting chip thickness. In accordance with the ductility of chip, the limiting chip thickness for Cr-Mo steel is thicker and that for 18-8 stainless steel is thinner than that for carbon steel.

(6) Proper radius of chip flow circle R_c decreases the cutting force, thrust force and chip thickness. Excessively small R_c , however, increases them.

(7) The increases in R_c and the slant of chip-breaker θ and the decrease in chip thickness decreases the force acting on the chip-breaker.

(8) The yield stress of chip for the bending at its root decreases with the increase of the shear strain of the chip.

(9) The tensile strength of chip produced in

the usual cutting becomes twice that of the same material before cut, and is slightly varied with the shear strain.

Suitable chip-breaker can be, therefore, designed as follows:

When the material to be cut and the cutting conditions are given, a trial cut gives the chip thickness for the conditions. The limiting value of R_c for chip breaking is obtained from Fig. 13. For the reliability of chip breaking and the decrease in cutting force, R_c smaller than the limiting value by about 20% is recommended. Excessively steep slant of the chip breaker is dangerous causing a violent shock at the beginning of cutting, though it decreases the force acting on the chip-breaker. It is recommended, therefore, to keep the slant smaller than 60 deg. When R_c and the slant are determined, the width of a chip-breaker is calculated by Eq. (2).

When the material to be cut and the shape of the chip-breaker are given, the most suitable cutting condition can be obtained from Fig. 13 in the similar way.

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Discussion

I. INOKUMA: So frequently, we encounter the problem of the chip-breaker under heavier cutting condition as you selected, namely at larger depth of cuts and feeds.

Under these conditions, if the chip-breaker form is not properly selected, the cutting efficiency becomes very low, as shown in Fig. 15 of your paper.

In determining the proportion of the chip-breaker under these conditions, may I consider extending the curve in Fig. 13 of your paper.

Author's closure

For the heavier cutting condition than that in

the experiments of this paper, the slopes of the curves in Fig. 13 seem not to change abruptly, though Eq. (1) shows that the slope increases gradually with the approach of R_0 (and R_c) to R_L .

To be exact, experiments should be supplemented.

Instead of measuring the cutting force as in Fig. 15, the observation of the shape of broken chip helps to check the propriety of R_c . Proper R_c produces some semicircular chip, but excessively small R_c produces such a short chip as smaller than one-fourth of a circle.