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The Effect of the Diameter of Carbide Face-Milling Cutters on their Failures*

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The effects of the cutter diameter were studied in respect with the failures of carbide face-milling cutters in the wide range of cutting speed.

The results obtained from the experiments are studied in the first half of this paper, mainly on a theoretical basis that the failures concern the situation of the temperature cycles to which the vicinity of the cutting edge is subjected.

An analytical expression of the temperature cycles is introduced in the latter half, and it could also explain the experimental results.

1. Introduction

A selection of the cutter diameter for a face-milling operation needs a review of the shape of the work piece, the machine tool construction and a consideration of the fact that a larger cutter costs more for handling and regrinding. Also attention has to be paid to how the cutter diameter affects the tool life.

First half of this paper reveals how the cutter diameter affects tool breakages, and explains the effect from the view point of temperature cycle. In the latter half, an analytical expression of temperature cycle is deduced and the effect of cutter diameter on temperature cycle is discussed.

There are practically two kinds of cases. One case is when a larger diameter of the cutter can be employed than the width of the surface to be face-milled. The other case is when the cutter diameter can not exceed the width of the surface to be face-milled, and the surface has to be machined successively by several passes. The effect of cutter diameter on temperature cycle differs in each case. In the former case, since a variation in cutter diameter brings about that in engage angle, a variation in the intensity of the mechanical impact between the tool and the work follows. Moreover, that case involves a problem of what position is optimum for the workpiece in respect to the cutter.

So far as face-milling is concerned, tool breakages are generally classified into high speed breakages and low speed breakages⁽¹⁾. A safe face-milling operation is possible in a medium cutting speed range which is sandwiched between a higher and a lower speed ranges where both breakages readily occur. Each breakage is differently affected by the cutter diameter.

2. Procedure, equipments and materials for the experiments

Procedure Most series of experiments are dry face-milling without cutting fluid. A few experiments employed a cutting fluid. The work piece is located at such a position that the center of the width of it always may coincide with the center of the cutter. The cutter diameter varies with a constant width of cut (90.0mm) or with a constant cutting time ratio (0.3). The latter case also brings about a constant ratio of the width of the work piece to the cutter diameter or a constant engage angle. Employed pairs of cutter diameters and widths of cuts are listed in Table 1.

Table 1 Pairs of cutter diameters and work width
Test with constant width of cut

Cutter dia. mm	94	111	172.5	393	Work material
Width of cut mm	90.0	90.0	90.0	90.0	S 45 C
Cutting time ratio	0.40	0.30	0.175	0.075	
Engage angle	73°	54°	31.5°	13.5°	

Test with constant cutting ratio

Cutter dia. mm	94	111	172.5	Work material
Width of cut mm	76.0	90.0	142.5	0.4% Carbon steel
Cutting time ratio	0.30	0.30	0.31	
Engage angle	54°	54°	55°	

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Milling machine Hitachiseisakusho No.2 horizontal milling machine, main motor power 7.5 HP, spindle speed 33~2000 rpm, table speed 8~1000 mm/min.

Work material An S45C steel is used in the experiments with a constant width of cut, and a 0.4 % carbon steel, with a constant cutting time ratio. Their contents and hardnesses are listed in Table 2.

Cutter A lathe tool with a carbide insert of ST 2 (Igetalloy grade) mechanically clamped, it is attached to a cutter body so that they constitute a face-milling cutter. The tool geometry is : -5° radial rake, -5° axial rake, 5° peripheral relief, 5° face relief, 15° peripheral cutting edge angle, 15° face cutting edge angle and 0.8 mm nose radius.

Cutting fluid In a few tests where a cutting fluid is employed, an emulsion type cutting fluid is used as diluted with water 30 times. The fluid is fed on the circle of the cutter pass through nozzles from an air pressured vessel which is constantly pressured by a 1/2 HP fluid feed pump. Nozzles are located on a circle around the cutter, inclined to the cutter axis by 30 degrees and at 16 such positions that divide the circle into 16 equal arcs. Among the 16 nozzles, only there are used with others closed by plugs, so that the cutting edge can be cooled by the fluid only while it is actually cutting.

3. Effects on high speed breakages

3.1 General description of high speed breakages

High speed breakages occur with the passage of some time after a newly reground cutter is put to use. On the contrary, low speed breakages generally occur rather in a short time after it is put to use.

It is already revealed⁽¹⁾ that high speed breakages occur in several types and each type is due to a singular crack. A chipping from flank is caused by the propagation of a cross crack on rake face near the cutting edge or by a combination of this crack with a cross crack on the flank. When the cutting speed or feed per tooth is large, a cross crack on the rake face near the cutting edge predominates and a chipping from rake face determines the tool life. This crack is probably due to a fatigue of carbide tool material caused by an intermittent mechanical stress near the cutting edge at an elevated temperature. When the cutting speed or feed per

tooth is small, a cross crack on the flank predominates so that the tool life is determined by a chipping from the flank. Among this type of crack, one near the cutting edge is particularly ready to cause a chipping. Although the cause of such a crack is not understood yet, the fact that a cutting fluid promotes the propagation of a cross crack from the flank proves that this crack is also affected by the temperature cycle.

3.2 Results from experiments

Tool life Fig. 1 indicates numbers of cuts till high speed breakages occur under various cutter diameters when other cutting conditions are kept nearly constant. Each case forms a linear relations on logarithmic coordinates. The inclination for the line A is -1.8 and that for B, -0.92 . Transforming these tool lives into machined volumes gives the same inclination of -0.92 for A, but an increased one of $-1.8+1=-0.8$ for B because the width of cut is proportional to the cutter diameter in this case. Thus both inclinations are close to each other.

The tool life of a multi-bladed cutter may be inferred from the above results which are obtained with a single-bladed cutter. A carbide bladed face-milling cutter usually provides proportional blades to its diameter. (One blade per inch of nominal diameter for steel machining and 2~2.5 blades for cast iron machining.) Then multiplying above data for single-bladed cutters by the number of blades gives the inclination of machined volumes versus the cutter diameter. This yields 0.2 for A and 0.08 for B. It is practically assumed that more reduction

Cutter diameter mm

A : Cutting time ratio 0.3, work material 0.4 % carbon steel, cutting speed 232~276 m/min, feed 0.218~0.296 mm/tooth, depth of cut 1.5 mm

B : Width of cut 90.0 mm, work material S45C, cutting speed 196~214 m/min, feed 0.22~0.296 mm/tooth, depth of cut 1.5 mm

Fig. 1 Effect of cutter diameter for number of cuts till high speed breakage

Table 2 Contents and Brinell hardnesses of work materials

	C	Si	Mn	P	S	Cu	Cr	Brinell hardness
S 45 C	0.48	0.32	0.76	0.015	0.020	0.14	0.11	274
0.4 % Carbon steel	0.38	0.28	0.53	0.021	0.014	0.14	0.14	167

has to be considered for the above multiplied values when the cutter provides more blades. Then, the last two inclinations can be roughly considered to be close to zero. Though this is true so far as a constant cutting time ratio of 0.3 or a constant width of cut of 90.0 mm is concerned, applying this for other values of them brings about the following conclusion.

Whatever cutter diameter or width of cut is employed, if the cutter provides proportional blades to its diameter and the other cutting conditions (cutting speed, feed per tooth, depth of cut and tool geometries) are kept constant, the cutter can machine an almost constant volume of work material before high speed breakages of blades. But this is true so far as the center of the cutter always coincides with that of the width of cut.

3.3 Effect of the relative position of a work with a cutter on the tool life

Several researches have dealt with the effect of the engage angle on the tool life by using a far

larger cutter diameter than the width of cut and varying their relative position for various engage angles. Three examples of these studies are indicated in Table 3. These data coincidentally show that the tool life is likely to be short when the absolute value of the engage angle is large. So far as it is rather a small value, namely when the center of the cutter is not far from that of the work, the tool life is likely to be long.

The effect of engage angle introduced here is contrary to that obtained from the former constant width of cut tests with various cutter diameters. This difference can be explained by considering the effect of the temperature cycle. Namely, when a constant width of cut is employed with a constant cutter diameter which is far larger than the width of cut, a variation in their relative position does not abruptly affect the temperature cycle, but does only the impact of engagement. When the engage angle is larger in this case, the location of impact is closer to the cutting edge and this promotes occur-

Table 3

Author	Test condition			
H. Siebel ⁽²⁾		A	B	
	Work material	30 Cr Ni Mo 8	CK 45
	Width of cut	100 mm	60 mm	
	Cutter dia.	250 mm		
	Cutting speed	115 m/min	149 m/min	
	Feed	0.25 mm/tooth		
	Depth of cut	3 mm		
	Carbide grade	L 2		
Tool life	Flank wear breadth 0.4 mm			
F.W. Lucht ⁽³⁾	Work material SAE 1045	Radial rake -10°
	Width of cut 38.1 mm	Axial rake -10°		
	Cutter dia. 203 mm	Peripheral cutting edge 15°		
	Cutting speed 152 m/min	45° Chamfer $\times 0.79$ mm		
	Feed 0.21~0.37 mm/tooth	Tool life : breakage		
	Depth of cut 3.18 mm			
	Carbide grade carbolloy 78 B			
H. Takeyama ⁽⁴⁾ K. Yamada	Work material S 45 C	Axial rake 10°
	Width of cut 65 mm	Peripheral cutting edge 15°		
	Cutter dia. 200 mm	Tool life:		
	Cutting speed 165 m/min	Flank wear breadth		
	Feed 0.2 mm/tooth	0.6 mm		
	Depth of cut 1.5 mm			
	Carbide grade ISO P 30 Radial rake -10°			

rence of breakages as explained by Takeyama and Yamada⁽⁴⁾. On the other hand, when the engage angle is increased by decreasing the cutter diameter with a constant width of cut, the temperature cycle

Cutter diameter 94 mm, work material 0.4 % carbon steel, width of cut 76.0 mm, cutting speed 22 m/min (74 rpm), feed 0.284 mm/tooth, depth of cut 2 mm, cutting time 0.5 min. Left is a sectional view perpendicular to cutting edge

Fig. 2 Low speed breakage, not propagated

becomes higher due to a shortened non-cutting period, and the impact of engagement is reduced. Thus a cross crack on the rake face near the cutting edge becomes harder to propagate and, consequently,

Feed per tooth mm/tooth

Cutter diameter 172.5 mm, work material S45C, width of cut 90.0 mm, depth of cut 2 mm, cutting fluid 3 % emulsion, flow quantity 3 l/min

Fig. 3(a) Critical limit of low speed breakage for emulsion and dry

A. Constant cutting time ratio (0.3)	<p>94 mm diameter</p> <p>Cracks R & F → Chipping from rake face</p>	<p>111 mm diameter</p> <p>Cracks R & F → Chipping from rake face</p>	<p>172.5 mm diameter</p> <p>Cracks R & F → Chipping from rake face</p>
B. Constant width of cut (90.0 mm)	<p>94 mm diameter</p> <p>Cracks R & F → Chipping from rake face</p>	<p>172.5 mm diameter</p> <p>Unknown</p>	<p>393 mm diameter</p> <p>Crack F → Chipping from flank → Chipping from rake face</p>

Symbols for cracks

R : Cross crack on rake face near cutting edge

F : Cross crack on flank

Fig. 3(b) Conditions are same as Fig. 2

the tool life becomes longer.

4. Effects on low speed breakages

4.1 General description of low speed breakages

Low speed breakages generally occur in a short time after a newly reground cutter is put to use at too low a cutting speed. This breakage determines if safe operation is possible or not under a given condition. Fig.2 shows an example of a low speed breakage which has not propagated yet by subsequent breakages. A low speed breakage occurs without any relation to a crack.

Takeyama and Yamada⁽⁴⁾ state that one cause of this breakage is the built up edge or the chip which sticks near the cutting edge even in the non-cutting period. As the cutting edge engages with the work, such sticking material enlarges the impact and a breakage occurs. Such stickings are considered to occur especially at a low cutting speed because the temperature of tool-chip interface is low at the end of the cutting period. In this sense, the low speed breakage concerns the temperature cycle. In addition to the above cause, the nature of the carbide material that it is more sensitive to impact at a nearer temperature to the ambient (low temperature brittleness) is considered to affect this breakage.

As for the proof for the temperature sensitivity of this breakage, a comparison between the critical limits of the breakage, one with the cutting fluid and the other without it, is indicated in Fig.3. The experiments are conducted in the following way. Because of the nature of breakage, a short time after a tool is put to use is the problem. Then after machining 10 mm of the work length at a certain cutting speed, the tool is inspected for the breakage. If a chipping has not occurred, the tool is again

Work material S45C, width of cut 90.0 mm, depth of cut 2 mm

Fig. 4 Critical limit of low speed breakage for various cutter diameter

tested in machining another 10 mm at a lower cutting speed but with the same feed per tooth as before. Thus the cutting speed is lowered successively till a breakage occurs. After several such procedures with various feeds, a critical limit for the low speed breakage is obtained. Fig.3 shows that the cutting fluid raises the critical cutting speed. This is presumably because of the cooling effect of the cutting fluid which lowers the temperature cycle. The reason for this assumption is that were it not for the effect on temperature cycle, a lubricating effect of the cutting fluid would prevent a sticking of material and lower the critical cutting speed.

4.2 Results from experiments

Fig.4 shows the critical limits for various cutter diameters with a constant width of cut. A general tendency is that the low speed breakage occurs more readily with a larger cutter diameter except that the limits for the least two diameters behave inversely. The reasons for this tendency are assumed as follows.

(1) A larger cutter diameter results in a smaller engage angle. Thus the impact of the engagement is enlarged.

(2) Since a longer non-cutting period follows a larger diameter, the cutting edge is cooled more in the period. Therefore, low temperature brittleness appears.

(3) As the heating in cutting period begins from such a low initial temperature, the cutting edge does not attain a sufficiently high temperature to prevent a sticking of material.

On the other hand, a variation in the cutter diameter with a constant cutting time ratio reveals

Work material 0.4% carbon steel, cutting time ratio 0.3, depth of cut 2 mm

Fig. 5 Critical limit of low speed breakage for various cutter diameter with constant cutting time ratio

an inverse tendency that a larger diameter prevents the low speed breakage (Fig.5). As the engage angle is kept constant, the above reason (1) is ineffective here. But as a longer cutting period follows a larger diameter in this case, the end temperature of the period is higher so that a sticking of material is prevented. And as the cooling in non-cutting period begins from such a high initial temperature, the end temperature of this period is likely to be comparatively high and low temperature brittleness does not appear.

5. An analytical expression of the temperature cycle

5.1 Analytical deduction

The vicinity of a cutting edge is heated during the cutting period. During non-cutting period, it is not heated but cooled by heat dispersion. Such transient change of the tool chip interface temperature in each cycle is discussed in the following. A transient rise in cutting period and a transient fall in non-cutting period are combined so as to form a steady temperature cycle.

(i) Transient rise of the temperature. Concerning the transient temperature rise after the start of a cut, McFeron and Chao⁽⁵⁾ present a theoretical calculation together with an experimental result about an orthogonal peripheral milling. But since applying a concrete function to the transient temperature rise complicates the analysis, it is presented by a general time function as follows.

The average temperature of the tool-chip contact area in a steady stage after a sufficiently long cut depends mainly on the cutting speed V and the feed S . It is represented by a sign $\bar{\theta}^*(V, S)$. If a tool is at ambient temperature before a cut, the average temperature of the tool-chip contact area increases from zero (ambient temperature) as the cutting time passes, till it reaches $\bar{\theta}^*(V, S)$. This transient rise of the average temperature can be represented by the following equation.

$$\bar{\theta}(t) = F_1(t) \bar{\theta}^*(V, S) \dots \dots \dots (1)$$

In this equation, it is supposed that $t=0$ when the

cut starts, and that $F_1(t)$ is such a function that $F_1(0)=0$ and increases monotonously with t and tends to 1 when t tends to an infinity as shown in Fig. 6(a). In conventional measurements, the cutting temperature is known to reach a steady value in an instant. So $F_1(t)$ must be such a function that increases abruptly in the vicinity of $t=0$ and is practically 1 with a small value of t .

The average temperature of the tool-chip contact area is not zero just before a new cut is begun after the tool has already repeated several cuts. It is represented by $\bar{\theta}_B$ hereafter. In this case, the interval through which the average temperature can rise is $\bar{\theta}^*(V, S) - \bar{\theta}_B$ as shown in Fig. 6(b). Then the transient rise of the average temperature in this case may be represented as follows.

$$\bar{\theta}(t) = F_1(t) \{\bar{\theta}^*(V, S) - \bar{\theta}_B\} + \bar{\theta}_B \dots \dots \dots (2)$$

When the period of the cutter rotation is represented by T and the cutting time ratio by R , Eq. (2) represents the variation of the average temperature for

$$0 \leq t \leq RT \quad (\text{cutting period})$$

Therefore, $\bar{\theta}_E$ which represents the average temperature of the tool-chip contact area at the end of the cutting period is given by the following.

$$\bar{\theta}_E = \bar{\theta}(RT) = F_1(RT) \{\bar{\theta}^*(V, S) - \bar{\theta}_B\} + \bar{\theta}_B \dots (3)$$

(ii) Cooling during the non-cutting period.

The tool-chip contact area which has the temperature $\bar{\theta}_E$ at the end of the cutting period is cooled during the next non-cutting period by the surrounding air (or the cooling fluid) which is at ambient temperature. The average temperature change during this period $\bar{\theta}(t)$ [this is referred to as the first variable, namely this is (1), the dimension of which is deg] may depend on the following variables.

(2) The average temperature just before the cooling. $\bar{\theta}$ [deg]

(3) The thermal diffusibility of the tool material. $a = \lambda / c\gamma$ [$L^2 T^{-1}$], where c : Specific heat, λ : Heat conductivity, γ : Specific weight.

(4) The specific heat transfer coefficient between the tool material and the cooling medium. h [L^{-1}]

(5) Time from the beginning of the cooling. t [T]

The method of the dimension analysis is applied to solve the relation among these variables.

Number of variables = 5, number of dimensions = 3, number of π -terms = (number of variables) - (number of dimensions) = 2.

A first π -term is supposed as follows

$$\pi_1 = \frac{\bar{\theta}(t)}{\bar{\theta}_E^A a^B h^C}, [\text{deg} \cdot \text{deg}^{-A} L^{-2B} T^B L^C]$$

The unknowns A , B and C are given as

Fig. 6

$$A=1, B=0, C=0$$

$$\therefore \pi_1 = \bar{\theta}(t) / \bar{\theta}_E$$

The second π -term is similarly

$$\pi_2 = \frac{t}{\bar{\theta}_E D a^E h^F}, [T \text{ deg}^{-D} L^{-2E} T^E L^F]$$

$$\therefore \pi_2 = h^2 a t$$

As the relation between these π -terms should be $\pi_1 = F_2(\pi_2)$, namely

$$\bar{\theta}(t) / \bar{\theta}_E = F_2(h^2 a t)$$

This equation is rewritten as follows by shifting the origin of time t to the beginning of the cutting period.

$$\bar{\theta}(t) = \bar{\theta}_E F_2\{h^2 a t(t-RT)\}, t \geq RT \quad (4)$$

As shown in Fig. 7, this $\bar{\theta}(t)$ must be equal to $\bar{\theta}_E$ at the beginning of the non-cutting period and must decrease with t till it tends to zero at last. Therefore, $F_2(x)$ has to be such a function that $F_2(0)=1$ and monotonously decreases with x till it tends to zero at last.

h is generally a function of the velocity of the tool relative to the cooling medium. This equals to the cutting velocity in the case of milling. A higher velocity generally results in a larger h .

The temperature fall expressed by Eq. (4) continues as far as $RT \leq t \leq T$, namely during the non-cutting period. The average temperature at the end of this period is given as follows.

$$\bar{\theta}(T) = \bar{\theta}_E F_2\{h^2 a (1-R)T\} \quad (5)$$

During the next cutting period, the temperature rises again from the temperature which equals to Eq. (5)

(iii) The steady temperature cycle. After enough repetitions of the cutting and non-cutting period, the temperature cycle attains a steady stage as shown in Fig. 8. In this situation, Eq. (5) has to be equal to $\bar{\theta}_B$. Namely,

Fig. 7

Fig. 8

$$\bar{\theta}_B = \bar{\theta}_E F_2\{h^2 a (1-R)T\} \quad (6)$$

The pair of Eqs. (3) and (6) shows which is the lowest point and which is $\bar{\theta}_E$, the highest point of the temperature cycle in the steady stage. Additionally, the fluctuation in average temperature $\bar{\theta}_a = \bar{\theta}_E - \bar{\theta}_B$ is given. These are as follows.

$$\frac{\bar{\theta}_B}{\bar{\theta}^*(V, S)} = \frac{F_1(RT) F_2\{h^2 a (1-R)T\}}{1 - \{1 - F_1(RT)\} F_2\{h^2 a (1-R)T\}} \quad (7)$$

$$\frac{\bar{\theta}_E}{\bar{\theta}^*(V, S)} = \frac{F_1(RT)}{1 - \{1 - F_1(RT)\} F_2\{h^2 a (1-R)T\}} \quad (8)$$

$$\frac{\bar{\theta}_a}{\bar{\theta}^*(V, S)} = \frac{F_1(RT) [1 - F_2\{h^2 a (1-R)T\}]}{1 - \{1 - F_1(RT)\} F_2\{h^2 a (1-R)T\}} \quad (9)$$

These equations represent the effects of the heating and the cooling on the temperature cycle. That is to say, $F_1(RT)$ represents the effect of heating. A larger (closer to 1) $F_1(RT)$ means a severer heating. On the other hand, $F_2\{h^2 a (1-R)T\}$ represents the effect of cooling. A smaller (closer

Fig. 9

Fig. 10

to 0) value of it means a severer cooling.

5.2 Effect of cutter diameter on temperature cycle

It has been inferred from experimental results that both the highest temperature $\bar{\theta}_E$ and the lowest temperature $\bar{\theta}_B$ concern tool breakages. These temperatures are illustrated in stereographs in Fig. 9 and Fig. 10. Firstly it concerns where the cutter diameter increases with a constant width of cut. Although RT decreases a little when the diameter increases with a constant cutting velocity maintained, its effect on $F_1(RT)$ is practically negligible. On the other hand, an increase in $(1-R)T$ is so evident that $F_2\{h^2a(1-R)T\}$ decreases. Then the locus on the base of both figures becomes as indicated by a curve B. Therefore both $\bar{\theta}_E$ and $\bar{\theta}_B$ decrease as indicated by curves B' with an increasing cutter diameter. A fall of $\bar{\theta}_B$ is particularly evident. It is understood that although the temperature cycle repeats at a high range with a small cutter, enlarging the diameter brings about a fall of $\bar{\theta}_B$ which accompanies a slight fall of $\bar{\theta}_E$. A variation of temperature in this manner fully agrees with one inferred from the experimental researches about both low and high speed breakages in the first half of this paper.

In the case of a constant cutting time ratio R , an increase in cutter diameter increases both RT and $(1-R)T$ if a constant cutting speed is maintained. The locus on the base of the figures becomes as indicated by the curve A. Then the corresponding curves B' show that $\bar{\theta}_E$ increases while $\bar{\theta}_B$ decreases. The reason why the high speed breakage occurs more readily with a larger cutter is this increase in $\bar{\theta}_E$. The reason why the low speed breakage is prevented by a larger cutter is that a higher $\bar{\theta}_E$ prevents the sticking of material. The fall of $\bar{\theta}_B$ in this case is slower than that in the case of B. So the low temperature brittleness does not affect in this case. These results agree with those from experiments fairly well.

6. Conclusion

The diameter of the carbide face-milling cutter is studied in respect to the effect on tool failures.

Concerning the tool life which is determined by high speed breakages, the following are revealed. With any cutter diameter or any width of cut, if the cutter provides proportional blades to its diameter and other cutting conditions are kept constant, the cutter can machine an almost constant volume of work material before high speed breakages of blades. But this is true as far as the center of the cutter coincides with that of the width of cut.

Low speed breakage concerns the engaging impact, sticking materials in the vicinity of the cutting edge at a low temperature and the low temperature brittleness. The low speed breakage occurs more readily with a larger diameter for a constant width of cut, or with a smaller diameter for a constant cutting time ratio.

These results are explained by the conception of the temperature cycle. An analytical expression of the temperature cycle agrees with the above explanation.

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References

- (1) K. Okushima and T. Hoshi: This Bulletin p.317
- (2) J. Siebel: *Untersuchungen über das Stirnfräsen von Stahl mit Hartmetall*, (1958), S.68.
- (3) F.W. Lucht: *Trans. ASME*, Vol.68 (1946), p.151.
- (4) H. Takeyama and A. Yamada: *Jour. Soc. Prec. Mech. Japan*, Vol.26, No.11 (1960), p.674.
- (5) D.E. McFeron and B.T. Chao: *Trans. ASME*, Vol. 80 (1958), p.321.

Discussion

T. YANASE: (1) Which does the author think is the dominant factor to breakage of cutting edge, thermal stress or impact force? Can this be quantitatively determined?

(2) Suppose the thermal stress is mainly the cause to breakage of cutting edge. Then, which does the author think is the major cause, tension or compression? And in this case can there be any experimental verification?

(3) In a brittle material, whose compressive

strength is supposedly 4 to 5 times its tensile strength, if the thermal stress is considered the major cause to breakage, it follows that breakage will hardly occur in the process of cutting. How about this point?

J. KUMABE: (4) Was it not possible to make actual measurement of temperature cycle during cutting?

(5) The discussor thinks that the temperature distribution change near the cutting edge should also be analyzed.

(6) In the author's tests, only the ST 2 which is supposedly unfit for intermittent cutting is employed. Which does the author think has greater bearing on the tool life in practical jobs, the selection of proper diameter or the selection of proper tool material?

(7) The discussor understands that the term "low temperature brittleness" the author uses is usually applied for the expression of brittleness of material at less than 0°C.

A. WAKURI: (8) The author states that the carbide face-milling cutter comes to a failure after a certain period of working. How did the author detect such failure?

The discussor has come to know that the toughness of carbide contributes a great deal to the improvement of tool life. In this connection he would like to suggest a testing of tough grades by the author. Suppose that the milling cutter succumbs to the fatigue under repetition of heating and cooling, how about warming the cutting fluid?

Authors' Closure

(1) Breakage of the cutting edge occurs in many types each of which is due to a singular mechanism. As for the stresses which concern the breakages, one is a thermal stress and the other is a mechanical stress which accompanies the impact force or the cutting force. The authors' previous paper deals with the relations among types of breakages and stresses.

As for such breakages that relate to this paper, the chipping from the rake face is considered to be caused by the mechanical stress. But the chipping from the flank has many unknown features. Low speed breakages are presumably due to impacts.

Unknown mechanisms of the breakage occurrences will have to be inferred from such experiments in which various conditions will be examined in relation to the breakages.

(2) Although all the breakages cannot be related with the thermal stress, it is true that the thermal crack causes a breakage. Since the thermal crack is a thermal fatigue phenomenon, both tensile and compressive thermal stresses are considered to cause the crack. That is to say, since the fatigue

occurs due to plastic strains in the material, both the tensile and the compressive strains contribute to the fatigue. The above previous paper also presents discussions on this point together with a proof by a model test.

(3) The discussor is right as far as the breakage due to a thermal shock is concerned. But the thermal crack in the face-milling cutter is likely to be caused by a thermal fatigue. The thermal crack propagates gradually under repeated plastic strains at an elevated temperature. After the crack has propagated to a certain limit, the mechanical stress presumably overcomes the material and the crack propagates furthermore. So a final breakage is considered to occur during the cutting period.

(4) Experimental measurement of the temperature cycle will be possible if high precision is not demanded. Such measurement is now under preparation by the authors.

(5) If a variation in even the temperature change near the cutting edge could be known, a more precise analysis would be possible about the effect of the temperature.

(6) ST 2 is not always unsuitable for face-milling. It is rather preferred to P 30 for it maintains a better cutting ability until breakage.

A tool material for a practical job had better be selected in relation with the selection of the cutter diameter. When a far larger diameter than the width of cut is employed, for example, toughness is desirable rather than wear-resistance. But when the diameter is close to the width of cut, a hard wear grade had better be used rather than a tough one.

(7) The authors are confident that it is not always limited for sub-zero centi degree.

(8) The breakage occurs suddenly in using a cutter. A breakage lessens the sharpness of the edge. This appears with a characteristic noise, vibration or sparks. These signs of a breakage are easy to recognize as a single bladed-cutter is used.

A tougher grade will be effective when the trouble is due to an impact or too low a temperature cycle, for instance a low speed breakage.

Warming the cutting fluid may be effective with its lubricant effect promoted but with its cooling effect suppressed. The authors thank the discussor for his good suggestion.