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Study on Skiving Process* (Cutting Force and Workpiece Deflection)

By Keizo SAKUMA** and Hiromichi ONIKURA***

The properties of cutting force and workpiece deflection in skiving process are investigated experimentally. It is found that the ploughing force acting on a cutting edge has a large proportion of total cutting force. The recommended ranges of the nominal rake angle and the plan angle of a cutting tool are discussed with reference to tool forces and chip formation. From the viewpoint of stiffness, a workpiece supported with the fixed center is better than one with the revolving center at the tailstock and the countersink diameter of center hole should be taken as large as possible.

1. Introduction

The automatic lathe is widely used, because of its excellent features, i.e., high productivity and low production cost. Skiving method⁽¹⁾, which has been known as a special form-turning method on the automatic lathe, has many advantages in metal removal rate, surface quality and machining cost and is applied to mass production of small size components. In this process, a forming tool in an off-center position is fed tangentially to the periphery of the finished workpiece. The cutting process is non-stationary and the nature of the variation of cutting resistance is quite different from that in the conventional (on-center) form turning. The transitional behavior of the relative displacement between workpiece and tool during skiving is important from the aspects of the surface quality of finished workpiece and the stabilization of the cutting process.

In this paper, the properties of cutting forces and workpiece deflection are investigated analytically and experimentally. First, the cutting forces for straight cutting edge are analyzed. The effects of cutting conditions and tool geometry on tool forces are examined experimentally and the methods to improve the stability of the cutting process are discussed.

2. Analysis of cutting force

A case of cylindrical turning by the tool with an oblique straight cutting edge is investigated (refer to Fig.1). In this method, undeformed chip thickness t decreases monotonously from the beginning of

Fig.1 Skiving process
(cylindrical turning)

cut and becomes zero when the cutting edge passes just under the workpiece axis, thereafter the clearance face of the tool burrishes the work surface. Active rake angle γ , active clearance angle κ , active inclination angle i of the cutting edge and cutting speed v vary with the tool progress as well as along the cutting edge⁽²⁾. The working edge length l_c after n revolutions of workpiece from the start is given in the following;

- (1) $l_c = nf / \sin \phi$ for $0 \leq n \leq b \tan \phi / f$
- (2) $l_c = b / \cos \phi$ for $b \tan \phi / f \leq n \leq \sqrt{R^2 - e^2} / f$
- (3) $l_c = (nf - \sqrt{R^2 - e^2}) / \sin \phi$ for $\sqrt{R^2 - e^2} / f \leq n \leq (\sqrt{R^2 - e^2} + b \tan \phi) / f$

.....(1)

where b is the cutting width, R , e , the radii before and after cutting, f the feed rate and ϕ , the plan angle of the cutting edge respectively. The variation of l_c is shown in Fig.4. It is assumed for simplification of calculation that the concentrated cutting force acts at the middle point of the active part of the cutting edge and that the cutting parameters at that point are used in the formulae as representative values.

According to the simple shear plane theory^{(3),(4)} of cutting force, the relationships between the shear force F_s and the

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** Professor, Kyushu University, Fukuoka.

*** Lecturer, Kyushu University.

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tool force components are given by the following;

$$\begin{aligned}
 [F_V]_s &= \left[\frac{\sin \delta c \cos \alpha n}{\tan \delta c} \right. \\
 &\quad \left. - \frac{\sin \alpha n [\cos \delta s + \sin (\zeta n + \theta n - \alpha n) \cot \delta c \sin \delta s]}{\cos (\zeta n + \theta n - \alpha n)} \right] F_s \\
 [F_H]_s &= \left[\frac{\sin \delta s [\cos \delta c \sin \alpha + \sin (\delta c - \xi) \sin \phi]}{\sin \delta c \cos \xi} \right. \\
 &\quad \left. + \frac{\cos \alpha n \cos \phi [\cos \delta s + \sin (\zeta n + \theta n - \alpha n) \cot \delta c \sin \delta s]}{\cos (\zeta n + \theta n - \alpha n)} \right] F_s \\
 [F_T]_s &= \left[- \frac{\sin \delta s \sin (\delta c - \xi) \cos \phi}{\sin \delta c \cos \xi} \right. \\
 &\quad \left. + \frac{\cos \alpha n \sin \phi [\cos \delta s + \sin (\zeta n + \theta n - \alpha n) \cot \delta c \sin \delta s]}{\cos (\zeta n + \theta n - \alpha n)} \right] F_s
 \end{aligned}
 \quad \dots \dots \dots (2)$$

where $[F_V]_s$, $[F_H]_s$ and $[F_T]_s$ are vertical, horizontal and transverse force components respectively, and τs and $A s$ are the shear stress and the area of shear plane satisfying the following relations;

$$F_s = \tau s A s \quad \dots \dots \dots (3)$$

$$A s \cong \int_{c_1}^{c_2} \frac{f \sin \theta}{\sin \zeta} \sqrt{\sin^2 (\theta + \zeta) + \cot^2 \phi} dz \quad \dots \dots (4)$$

Here, α : a nominal rake angle on the plane normal to the workpiece axis, αn : a nominal rake angle on the plane normal to the cutting edge, ηc : a chip flow angle defined on the rake face, δc : the direction angle of the friction force on the rake face, ηs : the direction angle of shear strain on the shear plane, δs : the direction angle of shear force on the shear plane, θ : the position angle of the cutting point, c_1 , c_2 : the minimum and the maximum longitudinal limits of the cutting portion of the cutting lip. The relations between the shear angle ζ and the normal shear angle ζn and between the position angle θn on the plane normal to the cutting edge and θ are given as follows;

$$\zeta n = \tan^{-1} \left[\frac{\tan \zeta \sin \theta n}{\sin \theta} \right] \quad \dots \dots \dots (5)$$

$$\theta n = \tan^{-1} \left[\frac{\tan \theta}{\cos \phi} \right] \quad \dots \dots \dots (6)$$

$$\eta s = \tan^{-1} \left[\frac{\tan \phi \cos (\zeta n - \alpha n + \theta n) - \tan \eta c \sin \zeta n}{\cos (\alpha n - \theta n)} \right] \quad \dots \dots \dots (7)$$

$$\xi = \cos^{-1} \left[\frac{\cos \alpha}{\cos \alpha n} \right] \quad \dots \dots \dots (8)$$

$$\alpha n = \tan^{-1} (\tan \alpha \cos \phi) \quad \dots \dots \dots (9)$$

Here, it is assumed that

- (a) cutting ratio is constant during cutting⁽²⁾
- (b) $\eta c = \phi$
- (c) $\eta c = \delta c$, $\eta s = \delta s$
- (d) work material yields according to von Mises' criterion.

The estimated value based on the above mentioned will be compared with the measured value.

The tool force is considered to consist of two components, i.e., (a) the cutting force transmitted through the rake face and (b) the ploughing force^{(5),(6)} acting on the cutting edge. The latter force may be attributable to the minute roundness of a cutting edge. And it is supposed that

- (a) the stress distribution form is ellipsoidal and the maximum stress value is equal to the Brinell hardness number (H_B)
- (b) the width of stress distribution is $2r$ (r being the radius of the cutting edge roundness)
- (c) the resultant force on a cutting edge is oriented to the bisector of a tool wedge angle⁽⁶⁾.

Then the force elements due to the ploughing force P are given by the following expressions;

$$\begin{aligned}
 [F_V]_p &= P \sin \nu \\
 [F_H]_p &= P \cos \nu \cos \phi \\
 [F_T]_p &= P \cos \nu \sin \phi
 \end{aligned}
 \quad \dots \dots \dots (10)$$

where ν is an angle between P and the horizontal plane. Therefore, the total force components are given by

$$\begin{aligned}
 F_V &= [F_V]_s + [F_V]_p \\
 F_H &= [F_H]_s + [F_H]_p \\
 F_T &= [F_T]_s + [F_T]_p
 \end{aligned}
 \quad \dots \dots \dots (11)$$

where $P = \pi H_B l c r / 2$.

3. Experimental procedures

Experiments were performed with carbide-tipped tools (P20), using a lathe (Model, 360HB-X, Japan-Cazeneuve). Tools having orthogonal straight edge ($\phi = 0^\circ$) as well as oblique straight edge ($\phi \neq 0^\circ$) were used. Work materials tested are carbon steel (S55C; yield stress $\sigma_s = 43 \text{ kg/mm}^2$, BHN $H_B = 203 \text{ kg/mm}^2$) and duralumin (17S; $\sigma_s = 30 \text{ kg/mm}^2$, $H_B = 102 \text{ kg/mm}^2$). And the periphery of a cylindrical workpiece, which was supported at one end by the chuck and at the other end mainly by the revolving center, was skived as shown in Fig.1. Cutting speed v was chosen in the range from 60 to 200 m/min at the periphery of the workpiece before cutting and feed rate f was 0.05~0.3 mm/rev. And the sulphur-chlorinated oil (Yusiro DS50) was supplied to the clearance side of tool. Cutting forces were measured by strain gauges bonded on the surfaces of the tool shank and recorded on the oscillograph, through a strain amplifier. Horizontal component δx and vertical component δy of workpiece deflection were measured by an inductance type micro-gap sensor and recorded.

4. Experimental results and discussions

4.1 The variations of cutting force and its orientation

(a) Orthogonal cutting

In this paper, skiving by a tool with zero plan angle is called ORTHOGONAL CUTTING and others OBLIQUE CUTTING. In orthogonal cutting, the horizontal cutting force component F_H rises sharply, reaches the maximum value after several revolutions of workpiece and after that decreases nearly in proportion to the amount of the undeformed chip thickness $t^{(2)}$ (refer to Fig.2). The vertical component F_V also rises after the beginning of cut, and in most cases F_{Hmax} is several times as large

Fig.2 The variations of cutting force and its direction (orthogonal cutting)

as F_{Vmax} . Afterwards F_V is almost constant and/or gradually decreases to zero where cutting terminates. However, on account of the effect of burnishing action by the tool clearance face, F_V hardly vanishes even after the cutting point passes just under the workpiece axis. The orientation of resultant cutting force is expressed by the following two angles,

$$\left. \begin{aligned} \psi_v &= \tan^{-1}(F_V/F_H) \\ \psi_T &= \tan^{-1}(F_T/F_H) \end{aligned} \right\} \dots\dots\dots (12)$$

Fig.3 The direction of resultant cutting force

as shown in Fig.3. As shown by the broken line in Fig.2, ψ_v gradually increases as the tool travels except in the transitional first period. Namely, the resultant force gradually changes the direction from horizontal to vertical, where $\psi_T=0^\circ$ because $F_T=0$.

(b) Oblique cutting

Cutting forces in oblique cutting increase more slowly and reach their peaks than in orthogonal cutting, as shown in

Fig.4 The variations of cutting force and its direction (oblique cutting)

Fig.4. The horizontal component F_H takes the largest value of the three components, and reaches the maximum at the particular instant when the full width of a cutting edge begins to be engaged in cutting. The variation of F_H is similar to that of cutting area. Transverse component F_T becomes maximum earlier than F_H and F_V takes the peak value later than F_H . In the case of duralumin, F_V keeps almost constant during cutting over the whole width of a cutting edge, the variation of which is different from those of the other two. This is due to the strong effect of ploughing force on vertical component. The reason is verified by the fact that an increase in edge roundness of tool causes an equal amount of increase in the maximum values of F_V and F_H in orthogonal skiving, i.e. the direction of the resultant force tends to be downward (refer to Fig.5). The

(a) The effect of edge roundness on cutting force components

(b) The effect of edge roundness on the direction of resultant force

Fig.5 The relation between cutting forces and edge roundness

variation of the direction of resultant force in oblique cutting is shown in Fig.4. As the tool advances, ψ_v increases and ψ_T decreases gradually. In other words, the direction of the resultant force tends to be downward.

4.2 The relationship between cutting forces and cutting parameters

The effect of feed rate on the maximum cutting force components are summarized in Fig.6. Cutting force vs. feed

Fig.6 The relation between cutting forces and feed rate

rate relation in this method is similar to cutting force vs. depth of cut relation in ordinary cutting, because undeformed chip thickness is roughly proportional to feed rate and the size of cutting area. The increase of feed rate causes a significant increase of F_{Hmax} and a small increase of F_{Vmax} and F_{Tmax} .

Fig.7 The effect of cutting speed on cutting forces

The effect of cutting speed on cutting forces is shown in Fig.7, which shows that increasing the cutting speed from 60 to 200 m/min results in a slight increase of cutting forces at the feed rate of 0.1 mm/rev and that the cutting forces with the feed rate of 0.2 mm/rev reach maximum at about 150 m/min. This fact seems to be due to the differences of the BUE size and the contact condition between chip and tool face.

The relation between cutting force and nominal rake angle is given in Fig.8. In general, an increase of rake angle α causes a decrease of three cutting force components F_V , F_H and F_T , but at the rake angle of greater than 30° , cutting process tends to be unstable due to the small value of F_V during cutting. A rake angle of greater than 30° is not desirable from the viewpoint of edge strength against chipping and wear resistance of the cutting edge. On the other hand, the minimum value of α is necessarily to be determined in accordance with the condition of the initial active rake angle γ_i , being greater

Fig.8 The relation between cutting force and nominal rake angle

than -10° . At the start of contact of the cutting edge with the workpiece, γ_i is given by $\gamma_i = (\alpha - \theta_i)$. Thus,

$$\gamma_i = \alpha - \theta_i \geq -10^\circ, \dots\dots\dots(13)$$

where

$$\theta_i = \cos^{-1}(e/R). \dots\dots\dots(14)$$

From Fig.2 and Fig.4 it is apparent that a non-zero plan angle ϕ can prevent a sharp rise of cutting force. An increase of plan angle ϕ causes a slight increase of F_{Hmax} and F_{Tmax} , as shown in Fig.9.

Fig.9 The relation between cutting force and plan angle

This result appears to be contradictory to the result⁽²⁾ reported before in which it was shown that the maximum cutting area decreases as the plan angle increases. However, as the whole length l of the cutting edge increases with an increase in plan angle ϕ according to

$$l = b / \cos \phi, \dots\dots\dots(15)$$

an increase in the total force can be expected, resulting from the effect of the ploughing force being proportional to the cutting lip length. On the other hand, increasing the plan angle ϕ results in an increase of the required length of tool travel and cutting time. It is desirable to select the plan angle ϕ in the range from 15° to 25° taking the smooth chip flow into consideration.

4.3 Comparison of theoretical estimates to experimental results

The cutting forces calculated using the equations (2) and (11) derived in the foregoing analysis are shown by the dot-dash line and the broken line respectively in Fig.10. Comparing with the measured values (solid line), it is found that the estimated values (11), for the case in which the ploughing force is being taken into account, gives better estimation than eq.(2). This can be vividly seen, particularly in the case of the estimation of F_v . Generally in skiving process undeformed chip thickness is relatively small. Therefore, the so-called size effect⁽⁷⁾ of cutting force is observed. The difference in the peak points between the calculated and the measured values appears to be due to the relative displacement between tool and workpiece.

Fig.10 The comparison between the measured value and the calculated value

4.4 Workpiece deflection during skiving

The tool and the workpiece deflect or sometimes vibrate in this process as well as in the conventional form turning. Especially near the end of cutting, the direction of the vertical deflection or vibration is normal to the finished surface and is likely to influence the surface quality, geometrical form and dimensional accuracy. In this experiment, the workpiece deflection only was measured, as the tool deflection was very small. An example of the variations of workpiece deflection components is given in Fig.11, where the variations of horizontal deflection δ_x and vertical deflection δ_y are similar to those of F_H and F_v (refer to Fig.4). Generally δ_{xmax} is several times as large as δ_{ymax} .

Fig.11 The variation of workpiece deflection

and often reaches 100 or 200 μm . However, since vertical deflection δ_y is at most 10 μm even in skiving S55C at 0.3 mm/rev, dimensional accuracy of diameter is presumed to be kept in the desirable region. It is one of the excellent features of this method.

The result of the static stiffness test of a supported workpiece (S55C) on a lathe is shown in Fig.12. The workpiece diameter D is 40 mm and the set overhang length of workpiece from the chuck end L_w is 80 mm. The portion of minimum stiffness is observed to be in the end of workpiece at the side of the revolving center. In the cutting test, when workpiece deflection becomes large, chatter vibration is liable to arise especially in cutting part ①. As L_w/D ratio increases and the elastic modulus of workpiece decreases, the minimum point of stiffness approaches towards the chuck. From the above mentioned and the compliance curve in Fig.12, it is very important to make the machine spindle more stiff.

Fig.12 Static stiffness test

The relation between the vertical deflection δ_y and the normal rake angle α_n is shown in Fig.13. Increase in α_n results in a slight decrease of δ_{ymax} , which corresponds to the variation of F_v . Nominal rake angle should be determined as a compromise among the decrease of vertical deflection, the stability of cutting process and the strength of a cutting edge.

Fig.13 The effect of nominal rake angle on vertical workpiece deflection

4.5 Improvement of the stiffness of workpiece supporting system

The comparison between a revolving center and a fixed center with regard to workpiece deflection, was performed as shown in Fig.14. It is shown that both deflection components, i.e. δx and δy with a revolving center are about half as large as those with a fixed center, namely the increase of stiffness is recognized.

Fig.14 The comparison of deflection between a revolving center and a fixed center

Using this fixed center the effect of the countersink diameter of center hole on the workpiece deflection was investigated. Fig.15 shows that an increase of this countersink diameter from 7.7 to 9.9mm results in a reduction of the maximum deflection. From $\delta x_{\max}=84\mu\text{m}$, $\delta y_{\max}=16\mu\text{m}$ to $\delta x_{\max}=54\mu\text{m}$, $\delta y_{\max}=6\mu\text{m}$. This indicates that the countersink diameter of center hole is one of the important factors. From the viewpoint of the stability of cutting process and finishing accuracy, it is desirable to select a center drill of sufficiently large diameter.

Fig.15 The effect of center drill diameter on workpiece deflection

4.6 The stability of cutting process

It is considered that the factors causing chatter vibration in this method include forced ones, — e.g. the unbalance of power transmission system and the eccentricity of workpiece being held — and self-induced ones — e.g. the growth and breakage phenomenon of built-up edge and the relation between the natural frequencies of tool-work system and workpiece rotating speed. In this paragraph, problems with

respect to feed rate are discussed. Although the cutting processes were smooth in the case of feed rate of 0.1 and 0.2 mm/rev, a chatter vibration occurred in 0.05 mm/rev feed rate from the start of cut and it was found impossible to continue cutting. This is mainly due to the stick-slip phenomenon on the interface between the cutting edge and the work surface and due to the relative displacement between tool and workpiece. The former phenomenon appears to be similar to that in the case of cutting a slightly inclined surface in planing⁽⁸⁾. Another cause is the increase of instability due to the very small vertical deflection for the feed rate of 0.05 mm/rev (refer to Fig.16).

Fig.16 The relation between workpiece deflection and feed rate

5. Conclusions

From the above the following are concluded:

- (1) Cutting forces vary with the tool travel and become maximum when the whole width of a cutting edge begins to be engaged in cutting. The direction of resultant force tends to be downward under a burnishing action. The horizontal component F_H is generally larger than the other two.
- (2) In skiving process, where undeformed chip thickness is generally small, ploughing force occupies a large proportion of total cutting force and has a significant influence on the vertical component F_v . Therefore, in the estimation of cutting forces a better approximation can be obtained by taking the ploughing force into consideration.
- (3) The maximum value of cutting force is influenced by the size of BUE. The velocity region where the cutting forces are relatively high, shifts to the lower side under the effect of BUE as the feed rate increases.
- (4) An increase of a rake angle leads to a decrease of cutting force and workpiece deflection. However, rake angles greater than 30° are not desirable from the viewpoint of the strength against chipping and wear of a cutting edge and the stability of cutting process. On the other hand, the minimum selected value of nominal rake angle α is necessarily to be determined in accordance with the condition of the ini-

tial rake angle γ_i ($=\alpha-\theta_i$) being greater than -10° .

(5) Cutting forces increase a little as the tool plan angle increases, which appears to be due to the ploughing force. Plan angle ϕ is desirably set in a range from 15° to 25° when taking a smoother chip flow into consideration.

(6) The variation of workpiece deflection during cutting corresponds to that of cutting force. Since the vertical deflection δy is much smaller than the horizontal deflection δx , sufficient accuracy would be kept. Horizontal deflection δx is sometimes larger than $100\text{ }\mu\text{m}$, so it is important to raise the stiffness of workpiece supporting system.

(7) From the viewpoint of the improvement of stiffness, a workpiece supported with a fixed center would be more desirable than the one supported with a revolving center and the selection of a larger size center drill is recommended.

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