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On Milling Process Using a Plain Milling Cutter with Helix Angle*

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In milling process using a plain milling cutter with helix angle, three components of cutting force corresponding to the varying undeformed chip thickness are measured simultaneously and precisely by unique optical method, and the influences of helix angle on the variational configuration of cutting force in up milling and in down milling are discussed in detail.

Based on the experimental results, the mechanics of milling process using a plain milling cutter with helix angle is discussed from the viewpoints of apparent friction angle on tool face, chip flow direction and effective rake angle, and the role of helix angle of a cutter in milling process is clarified experimentally.

1. Introduction

In peripheral-milling process, a milling cutter with helix angle is often used in order to prevent a tool wear and failure and to avoid undesirable influences caused by an intermittent action of cutting force. The cutting force consists of three components, i. e., the horizontal component which acts in the direction of feed motion, the vertical component which acts upward to the arbor and the axial component which acts along the spindle. Since these three components of cutting force vary momentarily with varying undeformed chip thickness, cutting process comes to be performed under an unsteady three-dimensional condition (cf. Fig. 1).

It has been considered very difficult, however, to make an accurate and simultaneous measurement of three components of cutting force corresponding to varying undeformed chip thickness; it seems to be for this reason that no accurate measurement results dealing with cutting force have been published. Even in a steady three-dimensional cutting process such as turning and other machinings, a fundamental discussion on three cutting force components is considered to be still insufficient, although a chip flow direction has been measured and discussed by Stabler⁽¹⁾, Shaw, Cook & Smith⁽²⁾ and Russel & Brown⁽³⁾.

In this paper, the horizontal, the vertical and the axial component of cutting force will be measured precisely by means of a unique optical method, and the variational configurations of these three components under various cutting conditions will be discussed in detail. On the basis of the experimental result, furthermore, the cutting, the thrust and the axial component of cutting force, which have the important meaning for the discussion of cutting mechanics, will be calculated, and the mechanics of milling process using a plain milling cutter with helix angle will be discussed from a viewpoint of chip flow direction, apparent friction angle

Fig. 1 Geometry of milling process

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on tool face, effective rake angle and so on.

2. Experimental procedure

An arbor used in this experiment is the same as the one used in the previous paper^{(4)~(7)}. On one end of the arbor, a single-toothed plain milling cutter with helix angle is held. Up milling and down milling are performed with the tools having various helix angles and rake angles, where the tool material is high-speed steel.

The horizontal component F_H is determined from the horizontal deflection angle of the arbor end using the same optical system as in the previous paper^{(4)~(7)}. The vertical component F_V and the axial component F_S are measured by applying the method mentioned in the previous paper. This method will be explained in the following with reference to Fig. 2. The component F_V acts in such a direction as deflects the arbor upward. The component F_S deflects the arbor upward also or downward, and its direction depends upon the direction of tool rotation: in cutting of Fig. 2 (1) F_S deflects the arbor upward and increases the deflection of arbor which is caused by F_V ; on the other hand, in cutting of Fig. 2 (r) F_S deflects the arbor downward and decreases the deflection caused by F_V . Thus, defining V_V , V_S as the arbor deflections yield-

ed by F_V , F_S respectively, the total deflection in two cutting forms is represented by the following equations.

$$V_1 = V_V + V_S \quad \text{for Fig. 2 (1)}$$

$$V_r = V_V - V_S \quad \text{for Fig. 2 (r)}$$

It is ascertained as mentioned later that the increment and the decrement of vertical deflection yielded by F_S are almost equal under the same cutting condition. Thus, the mean value of vertical deflection $(V_1 + V_r)/2 = V_V$, which is given from the measured results in two cutting forms (1) and (r), represents the deflection caused by F_V alone, and $|V_1 - V_r| = |V_r - V_V| = V_S$ represents the deflection by F_S alone.

Figure 3 shows some examples of the experimental records of cutting force in up milling and in down milling using two cutting forms (1) and (r). The signs (1) and (r) in the figure correspond to Fig. 2 (1) and (r). In the figure, curved dot a, straight dots b and c represent the variation of cutting force, the stationary point for it and the angular displacement of tool, respectively. Using two experimental records (1) and (r) as a pair under the same condition, three components of cutting force F_H , F_V , F_S can be obtained by the method mentioned above.

Fig. 2 Method of measurement of cutting force

Fig. 4 Cutting force calibration diagram

Fig. 3 Experimental records ($\alpha=0^\circ$, $\lambda=50^\circ$)

Figure 4 shows the applied force calibration diagram against film displacement when the axial force F_s is applied to cutting edge from left side and right (l), (r), for the purpose of discussing the adequacy of the method to obtain F_v , F_s . The relationships between the film displacement and the applied force in both forms (l), (r) are in good proportion, and both are in good agreement with each other. As shown in the figure, furthermore, the straight line is also in good agreement with the same sort of experimental data derived under the condition of constant loading of horizontal force $F_H=100$ kg and vertical force $F_V=50$ kg. It is thus recognized that F_s can be obtained accurately without any interference with F_H and F_V . It is ascertained by the more loading tests about F_H , F_V that three components of cutting force can be measured very accurately without a mutual interference.

On the basis of cutting forces F_H , F_V , F_s measured corresponding to the varying undeformed chip thickness, the cutting component F_T , the thrust component F_N and the resultant cutting force F can be obtained as shown in Figs. 1 and 5. Moreover, the normal component to rake face N , the tangential component in rake face T of resultant cutting force F , the apparent friction angle θ_1 and the angle θ_2 which is intimately related to chip flow direction can also be acquired accurately.

3. Experimental results

The experiments are carried out on up milling and down milling using a single-toothed plain cutter with helix angle. The workpiece, the tool and other cutting conditions are shown in Table 1. Helix and rake angle of tool are changed, and all the experiments are made in dry cutting.

3.1 On F_H , F_V , F_s

Figures 6~9 show some examples of the experimental results on F_H , F_V , F_s obtained corresponding to the angular displacement of tool φ . These are obtained through the experimental records like Fig. 3 by using the method explained in the previous

Fig. 5 Components of cutting force and its direction

section. The angular displacement φ represents the angle of tool rotation, which is measured at the center of tool edge as shown in Fig. 1. The lines A'D', D'E' denoted by dot-and-dash lines show the variation of the mean undeformed chip thickness t at every moment. Point A', E' in the figures show the starting and the finishing position of cutting process respectively. The angular displacements at both points are changed by tool helix angle as follows.

$$\varphi_A' = -\frac{b}{2R} \tan \lambda, \quad \varphi_E' = \varphi_E + \frac{b}{2R} \tan \lambda \quad \dots (1)$$

where φ_A , φ_E show the angular displacements of tool at the points A, E in Fig. 1, that is, the starting and the finishing position determined at the center of tool edge. The maximum undeformed

Table 1 Cutting conditions

Tool (Single tooth)	High speed steel
	Helix angle $\lambda = 0^\circ, 15^\circ, 25^\circ, 35^\circ, 50^\circ$
	Rake angle $\alpha = -5^\circ, 0^\circ, 10^\circ, 20^\circ$
	Clearance angle $\beta = 9^\circ$
Workpiece	Cutter radius $R = 54.7$ mm
	S35 C, Tensile strength 59.5 kg/mm ²
Cutting conditions (Dry cutting)	Cutting speed $v = 4.1$ m/min
	Width of cut $b = 3 \pm 0.02$ mm
	Depth of cut $d = 3$ mm
	Feed per tooth $f = 0.35$ mm

Fig. 6 Variation of F_H , F_V , F_s ($\alpha=0^\circ$, $\lambda=25^\circ$)

Fig. 7 Variation of F_H , F_V , F_s ($\alpha=0^\circ$, $\lambda=50^\circ$)

chip thickness t_D' and the corresponding angular displacement φ_D' where the maximum undeformed chip thickness is reached are calculated from the following equations,

$$t_D' = t_D \left\{ 1 - \left(\frac{1}{\varphi_E} - \frac{1}{2\varphi_D} \right) \frac{b}{2R} \tan \lambda \right\} \dots\dots\dots (2)$$

$$\varphi_D' = \varphi_D \left\{ 1 - 2 \left(\frac{1}{\varphi_E} - \frac{1}{2\varphi_D} \right) \frac{b}{2R} \tan \lambda \right\} \dots\dots\dots (3)$$

where t_D is the undeformed chip thickness at point D in Fig. 1 and φ_D is the angular displacement of tool at D. t_D corresponds to the maximum undeformed chip thickness in the case of plain milling with straight edge (i. e., the case of $\lambda=0^\circ$), and φ_D corresponds to the angular displacement at t_D in the same case. As obviously understood from Eqs. (1) ~ (3), φ_E' increases with an increase in helix angle λ , while the maximum undeformed chip thickness t_D' and the position φ_D' decrease with an increase in ν .

Examination of Figs. 6 ~ 9 under consideration of the above mentioned, shows that the values of F_H , F_V , F_S and their variational configurations in both up milling and down milling are remarkably affected by tool helix angle λ and tool rake angle α .

First comparing Fig. 6 with 7 for a small rake angle $\alpha=0^\circ$, the value of F_H in both up milling and down milling decreases generally with an increase in helix angle, especially at later stage of cutting in up milling. Because of that, the maxi-

um value of F_H in up milling, i. e., $(F_H)_{\max}$, decreases by 25 ~ 30 % with an increase in helix angle from $\lambda=25^\circ$ to 50° , while $(F_H)_{\max}$ in down milling decreases only by 8 %. A similar tendency is seen for F_V also; e. g., when $\lambda=50^\circ$, F_V in later stage of cutting in up milling is very small. The value of axial component F_S , on the other hand, increases considerably in both up milling and down milling with increased helix angle. It is further seen that F_S in down milling is larger than that in up milling for a small helix angle $\lambda=25^\circ$, but as helix angle increases to reach $\lambda=50^\circ$, the value and the variational configuration of F_S in down milling come to agree with those in up milling.

Secondly, comparing Figs. 8, 9 in which F_H , F_V , F_S are obtained for the case of a large rake angle $\alpha=10^\circ$ with Figs. 6, 7 ($\alpha=0^\circ$), it is seen that both F_H , F_V in up milling and down milling decrease considerably with increased rake angle. However, for a large rake angle in Figs. 8 and 9, F_H , F_V in both millings do not vary so remarkably in spite of an increase in λ as seen in Figs. 6, 7 ($\alpha=0^\circ$). It is found that the axial component F_S does not depend upon tool rake angle, but is deter-

Fig. 8 Variation of F_H , F_V , F_S ($\alpha=10^\circ$, $\lambda=25^\circ$)

Fig. 9 Variation of F_H , F_V , F_S ($\alpha=10^\circ$, $\lambda=50^\circ$)

Fig. 10 Relation between $(F_H)_{\max}$, $(F_V)_{\max}$, $(F_S)_{\max}$ and helix angle ($\alpha=0^\circ$)

Fig. 11 Relation between $(F_H)_{\max}$, $(F_V)_{\max}$, $(F_S)_{\max}$ and helix angle ($\alpha=10^\circ$)

mined only by helix angle.

Figures 10, 11 show the values of $(F_H)_{\max}$, $(F_V)_{\max}$, $(F_S)_{\max}$ in both up milling and down milling against helix angle λ . It is seen in Fig. 10 for $\alpha=0^\circ$ that $(F_H)_{\max}$, $(F_V)_{\max}$ in both up milling and down milling decrease with increased helix angle in general. This tendency is especially remarkable in up milling in the range of $\lambda=25^\circ \sim 50^\circ$ as also shown in Figs. 6, 7, while in the range of $\lambda \leq 25^\circ$ little effect of helix angle is found. Next, $(F_S)_{\max}$ is seen to increase approximately proportion to helix angle, except in $\lambda \leq 25^\circ$ where $(F_S)_{\max}$ in down milling is considerably larger than that in up milling.

On the other hand, in Fig. 11 for a larger rake angle $\alpha=10^\circ$, quite different effects of helix angle from the case of $\alpha=0^\circ$ on $(F_H)_{\max}$, $(F_V)_{\max}$, $(F_S)_{\max}$ are found unlike; $(F_H)_{\max}$ is nearly constant independently of helix angle in up milling and in down milling, and $(F_V)_{\max}$ in up milling scarcely changes while $(F_V)_{\max}$ in down milling decreases remarkably at large rake angle. Moreover, agreement is seen between the values of $(F_S)_{\max}$ in up milling and those in down milling, both of which increase approximately in proportion to helix angle.

On the basis of variational configurations of F_H , F_V , F_S and some tendencies of $(F_H)_{\max}$, $(F_V)_{\max}$, $(F_S)_{\max}$ mentioned above, it becomes possible to

Fig. 12 Variation of F_T , F_N , F_S ($\alpha=0^\circ$, $\lambda=25^\circ$)

Fig. 13 Variation of F_T , F_N , F_S ($\alpha=0^\circ$, $\lambda=50^\circ$)

discuss substantially the influence of cutting force upon the feed motion, the vertical vibration of arbor and the dynamic behavior of arbor in direction of spindle from a practical viewpoint^{(4)~(6)}.

3.2 On F_T , F_N , F_S

The cutting component F_T (tangential to tool-rotation) and the thrust component F_N (normal to tool-rotation) of cutting force can be calculated in the same manner as in the previous paper^{(4)~(7)} on the basis of F_H , F_V which are measured corresponding to angular displacement of cutter (cf. Fig. 1). Figures 12, 13 are examples of the variational configurations of F_T , F_N , F_S obtained corresponding to ϕ , where F_S curve is the same as shown in Figs. 6, 7. In the figures, it is seen that the value of F_T in both up milling and down milling decreases with increased helix angle, and that this tendency is more remarkable at and after the middle stage of cutting in both millings, i. e., in up milling at the stage where ϕ is larger, and in down milling at smaller ϕ .

From this result, the tendency in plain milling process using a straight edge ($\lambda=0^\circ$) shown in the previous paper^{(4)~(6)} (i. e., at the stage of smaller ϕ , F_T in up milling is smaller than that in down milling, and in contrast with this, at the stage of larger ϕ , F_T in up milling is fairly larger than that in down milling) is considered to disappear with an increase in helix angle, and when $\lambda=50^\circ$, F_T curves in both millings are seen to agree with each other. Furthermore, the angular displacement of cutter ϕ where cutting force F_T reaches the maximum value $(F_T)_{\max}$ becomes greater as helix angle increases. Since this tendency is especially remarkable in down milling, the values of angular displacement ϕ in both millings become almost equal at large helix angle, and both approach to $\phi_{D'}$ where the maximum undeformed chip thickness is yielded. These tendencies observed in F_T curve are recognized also in F_N curve.

Figures 14, 15 show the values of $(F_T)_{\max}$, $(F_N)_{\max}$, $(F_S)_{\max}$ which are obtained from F_T , F_N , F_S curve under various conditions. First, in Fig. 14 for $\alpha=0^\circ$, $(F_T)_{\max}$ in up milling is generally larger than that in down milling, and decreases remarkably with an increase in helix angle in the range of $\lambda=25^\circ \sim 50^\circ$. On the other hand, $(F_T)_{\max}$ in down milling shows only a little decrease in spite of an increase in helix angle, so that the values of $(F_T)_{\max}$ in both millings come into agreement with each other with increased helix angle λ . A decrement in $(F_N)_{\max}$ in the range of $\lambda=25^\circ \sim 50^\circ$ is seen to be larger than that in $(F_T)_{\max}$ both in up milling and in down milling.

Secondly in Fig. 15 for a large rake angle $\alpha=10^\circ$, a different inclination from $\alpha=0^\circ$ is seen;

$(F_T)_{\max}$, $(F_N)_{\max}$ in up milling are larger than those in down milling in the range of $\lambda=0^\circ \sim 25^\circ$, and agree with those in down milling at $\lambda=25^\circ \sim 50^\circ$.

Figures 16, 17 show the values of $(F_T)_{\max}$, $(F_N)_{\max}$, $(F_S)_{\max}$ in both up milling and down milling against tool rake angle α , for each case of $\lambda=25^\circ$, 50° . It is seen in Fig. 16 for a small helix angle $\lambda=25^\circ$ that $(F_T)_{\max}$, $(F_N)_{\max}$ in up milling are larger than those in down milling, and that a decrement in $(F_T)_{\max}$, $(F_N)_{\max}$ caused by an increase in rake angle is very large in up milling. Because of this, $(F_T)_{\max}$, $(F_N)_{\max}$ curves are seen to cross each other, while in Fig. 17 ($\lambda=50^\circ$) $(F_T)_{\max}$, $(F_N)_{\max}$ in both millings are nearly equal. In Fig. 17, furthermore, the degree of a decrease in $(F_T)_{\max}$, $(F_N)_{\max}$ with increased rake angle is considerably smaller as compared with the case of small helix angle $\lambda=25^\circ$.

3.3 On F , θ_1 , θ_2

An apparent friction angle θ_1 and an angle θ_2 which shows acting direction of tangential component in tool rake face T can be calculated from the following equations, on the basis of F_T , F_N , F_S experimentally obtained corresponding to the angular displacement φ .

$$F = \sqrt{F_T^2 + F_N^2 + F_S^2} \quad \dots\dots\dots (4)$$

Fig. 14 Relation between $(F_T)_{\max}$, $(F_N)_{\max}$, $(F_S)_{\max}$ and helix angle ($\alpha=0^\circ$)

Fig. 15 Relation between $(F_T)_{\max}$, $(F_N)_{\max}$, $(F_S)_{\max}$ and helix angle ($\alpha=10^\circ$)

$$\theta_1 = \cos^{-1} \left[\frac{(F_T \cos \lambda + F_S \sin \lambda) \cos \alpha - F_N \sin \alpha}{F} \right] \quad \dots\dots\dots (5)$$

$$\theta_2 = \tan^{-1} \left[\frac{F_T \sin \lambda - F_S \cos \lambda}{(F_T \cos \lambda + F_S \sin \lambda) \sin \alpha + F_N \cos \alpha} \right] \quad \dots\dots\dots (6)$$

Figures 18, 19 are examples of F , θ_1 , θ_2 obtained corresponding to φ for the case of helix angle $\lambda=25^\circ$ and 50° respectively. First, about the resultant cutting force F , it is seen by comparing Fig. 18 with Fig. 19 that the value of F decreases with increased helix angle both in up milling and in down milling, and this tendency is specially remarkable in up milling. In fact, in the case of $\lambda=50^\circ$, F in both up milling and down milling shows almost the same variational configurations. As helix angle becomes large, the angular displacement where F reaches the maximum value approaches the position where the maximum undeformed chip thickness is reached. Since this inclination is remarkable in down milling, it is seen for a large helix angle that the variational configurations of F in both millings come to agree with the variation of undeformed chip

Fig. 16 Relation between $(F_T)_{\max}$, $(F_N)_{\max}$, $(F_S)_{\max}$ and rake angle ($\lambda=25^\circ$)

Fig. 17 Relation between $(F_T)_{\max}$, $(F_N)_{\max}$, $(F_S)_{\max}$ and rake angle ($\lambda=50^\circ$)

thickness.

Secondly, the value of apparent friction angle θ_1 in up milling is considerably large at the early stage of cutting process and decreases rapidly with an increase in the undeformed chip thickness t , and after this, it holds nearly constant.

On the other hand, it seems in down milling that the value of θ_1 at the early cutting stage is fairly small, and increases gradually as cutting proceeds, reaching a nearly constant value. These constant values of θ_1 at the middle stage of cutting in up milling and in down milling are nearly equal. These variational configurations of θ_1 at the early cutting stages in both up milling and down milling are considered to show concretely the transitional behavior of cutting mechanics. Therefore, it is found from these figures that the period of transitional cutting process is shortened in both up milling and down milling as helix angle increases. This tendency is remarkable in down milling, so that it is seen in the case of $\lambda=50^\circ$ that a transitional state of cutting is finished as early as the time when cutting edge reaches the position of maximum undeformed chip thickness. This observation is considered to correspond to the fact that, when helix angle becomes large, the variational configuration of F in down milling comes to agree

Fig. 18 Variation of F , θ_1 , θ_2 ($\alpha=0^\circ$, $\lambda=25^\circ$)

Fig. 19 Variation of F , θ_1 , θ_2 ($\alpha=0^\circ$, $\lambda=50^\circ$)

with the variation of undeformed chip thickness.

In the third place, the variation of θ_2 in Fig. 18 ($\lambda=25^\circ$) presents a matter of some importance. It is seen in the figure that the value of θ_2 in down milling is generally smaller than that in up milling and is largely varied during cutting. This θ_2 value depends upon the component of cutting force F_s as easily found from Fig. 5 and Eq. (6); it decreases with increased F_s and increases with decreased F_s . Thus, the variation of θ_2 in down milling seen in Fig. 18 corresponds to the variation of F_s in Figs. 6 and 12 shown in the previous sections.

By considering here the fact that the variation of θ_2 in Fig. 18 is especially remarkable at the early and middle stages of cutting in down milling with small helix angle and rake angle, it seems to be certain that the aforementioned inclination is caused by a difficulty of chip flow along the tool edge, because the chip yielded at the early stage of down milling is very thick and unable to flow smoothly. And it is also well understood from the foregoing description that, as seen in Figs. 10 and 18, $(F_s)_{\max}$ in down milling with small helix angle and rake angle is larger than that in up milling but θ_2 is small.

In Fig. 19 for a large helix angle $\lambda=50^\circ$, on the other hand, the values of θ_2 both in up milling and in down milling are nearly equal. It is further found that the values of θ_2 in both millings increase remarkably with an increase in helix angle, and are approximately equal to the value of helix angle λ .

Figure 20 shows the mean value of apparent friction angle $(\theta_1)_m$ during the period where θ_1 is constant, i. e., a steady state has been reached after the transitional period in the early cutting stage. In the figure, $(\theta_1)_m$ increases with increased helix angle and this tendency is the same as that of $(\theta_1)_m$ increasing with an increase in rake angle. This fact seems to suggest that both the increases in helix angle and in rake angle play qualitatively equivalent roles in at least an apparent friction angle.

Figure 21 shows, moreover, the mean value of θ_2 , during period of steady state cutting stage, i. e., $(\theta_2)_m$ against helix angle. The broken straight

Fig. 20 Relation between $(\theta_1)_m$ and helix angle

line in the figure is quoted from the Stabler's experimental result⁽¹⁾ in which the chip flow direction in general three-dimensional steady cutting process is measured and approximated by a single straight line for each helix angle, and which is known as "Stabler's law". It is seen in the figure that the value of $(\theta_2)_m$ in this experiment is nearly equal to the value of helix angle λ and shows a considerably good agreement with the chip flow direction in the general three-dimensional steady cutting process. The value of $(\theta_2)_m$, on the other hand, has an intimate relation to the direction of chip flow. Therefore, the aforementioned result shows that even in the unsteady three-dimensional cutting process like this experiment, the chip-flow direction can be discussed from the same standpoint as in the steady three-dimensional cutting process except at the early transitional stage of cutting.

Figure 22 shows the effective rake angle α_e against helix angle, where α_e is the rake angle measured in a plane which includes the direction of

Fig. 21 Relation between $(\theta_2)_m$ and helix angle

Fig. 22 The effects of helix angle and rake angle on the effective rake angle α_e

tool-rotation (or feed of workpiece) and the chip flow direction. It is seen in the figure that the value of α_e increases with increased helix angle and this tendency is more remarkable at smaller rake angle, while α_e also increases with increased rake angle and this is also more remarkable at smaller helix angle. Thus the foregoing description supports, from a viewpoint of effective rake angle, the experimental result seen in F_T , F_N , F_S curves in the previous section, i.e., the smaller the rake angle, the larger the effect of helix angle on the cutting force is; and on the other hand, the smaller the helix angle, the more remarkable the effect of rake angle.

4. Conclusions

In the milling process using a plain milling cutter with helix angle, three components of cutting force are measured precisely corresponding to the undeformed chip thickness, and the effects of helix angle and rake angle of tool on the variational configuration of cutting force are investigated in detail. The main effects of helix angle obtained experimentally are as follows:

(i) As helix angle increases, the cutting component F_T and the thrust component F_N of cutting force decrease, and their decrement is especially large at and after the middle stage of cutting in up milling. The axial component F_S increases approximately in proportion to helix angle and is hardly influenced by rake angle.

(ii) The decrements of F_T , F_N caused by an increase in helix angle are remarkable in the range of larger helix angle $\lambda = 25^\circ \sim 50^\circ$. The decrement of F_N is considerably larger than that of F_T .

(iii) As helix angle increases, the variational configurations of F_T , F_N , F_S come into agreement with the undeformed chip thickness.

(iv) The smaller the tool rake angle, the more remarkable the effect of helix angle on cutting force becomes.

On the basis of experimental result, the apparent friction angle on rake face, the direction of chip flow and the effective rake angle are also discussed.

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Discussion

Y. ANNO, E. USUI (1) In the experiment, the angle of tool rotation (i.e., the angular displacement) seems to be measured at the end of main spindle of machine tool. It is considered, however, that the angle measurement is affected by an elastic torsion from the cutting edge to the end of main spindle. How is this effect considered?

(2) It is stated in this paper that, as helix angle increases, the variational configurations of F_T , F_N , F_S are in agreement with that of undeformed chip thickness. How can the above result be explained in technical meaning?

(3) Strictly considered, the variation of cutting force F_T , F_N seems to be related not to the undeformed chip thickness yielded at the cutting edge, but to the thickness at the point where a shear plane meets the workpiece surface. From this point of view, it is considered that the angular displacement where cutting force F_T , F_N reaches a maximum value should be smaller than ϕ_D' in down milling, and larger than ϕ_D' in up milling. In the case of $\lambda=25^\circ$, however, as compared with $\lambda=50^\circ$, the angular displacement where F_T , F_N reach a maximum is yielded at smaller angles in both millings. How do the authors consider the fact?

Authors' closure

(1) In this experiment, as shown in the previous paper⁽⁴⁾⁻⁽⁶⁾, an arbor which is 36 mm in diameter and 136 mm in length is made for convenience of measurement. On one end of the arbor, a milling cutter which is 54.7 mm in radius is mounted. Thus, the calculation of elastic twist angle from the cutting edge to the end of arbor gives $3'45''$ (0.001 rad) for the case in which the maximum cutting force (smaller than 200 kg in this experiment) is applied. This value is found very small, so even if the influence of irregularity in tool rotation caused by the torsion of arbor exists, it will negligible.

As the other cause of irregularity in rotation of milling cutter, a torsion of driving shaft (main spindle of turning lathe in this experiment) may be suspected. But the amount of twist angle is so small that it can be neglected. In fact, it is found

in the experimental records in Fig. 3 that the revolution marks c which record the angular displacement of the end of main spindle at intervals of 1.5° are arranged at the same spacing on film.

(2) The statement made (the 8th line in the right side of p. 580, (iii) in conclusion in p. 582) represents the fact that the variational configuration of cutting force varies remarkably with increased helix angle. It may be possible to explain the reason for the fact as follows. The milling process usually has a transitional feature in the variation of undeformed chip thickness. The influence of this transitional feature on primary factors constituting the cutting force (cf. the previous paper⁽⁵⁾⁽⁶⁾) is considered to become smaller with an increase in helix angle or rake angle. Thus, it is concluded that, as helix angle or rake angle increases, the value of cutting force at each undeformed chip thickness comes into agreement with that at the same thickness in a steady three-dimensional cutting process. The statement has been made on the basis of the above consideration.

(3) It is exactly as pointed out by discussers that the cutting force depends upon the undeformed chip thickness at the point where a shear plane meets the workpiece surface. However, the difference between this undeformed chip thickness and the thickness at the cutting edge is very small. For example, calculating the difference in the case of the so-called shear plane angle 30° and the undeformed chip thickness at the cutting edge 0.12 mm (which is the maximum value in this experiment), we find that the undeformed chip thickness at the cutting edge is larger by about 1.4×10^{-3} mm in up milling and smaller by about 1.4×10^{-3} mm in down milling. These values, however, are only 1% of the undeformed chip thickness. Thus, only 3.8×10^{-3} rad difference exists between the angular displacement where the cutting force reaches its maximum in up milling and down milling. It is concluded from the consideration of the above that the influence upon the angular displacement where F_T , F_N reach maximum is not so large as pointed out in the discussion.