In-process Estimation of Radial Immersion Angle Using Cutting Force in Face Milling

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In this paper, a on-line estimation method of the radial immersion angle using cutting force is presented. The ratio of cutting forces in feed and cross-feed directions acting on the single tooth at the immersion angle is a function of the immersion angle and the ratio of radial to tangential cutting force. It is found that the ratio of radial to tangential cutting force is not affected by cutting conditions and axial rake angle, which implies that the ratio determined by one preliminary experiment can be used regardless of the cutting conditions for a given tool and workpiece material. Using the measured cutting force during machining and predetermined ratio, the radial immersion ratio is estimated in process. Various experimental results show that the proposed method works within 5% error range.

Key Words : Radial Immersion Angle, On-Line Estimation, Cutting Force Ratio, Face Milling

Nomenclature

ϕ	: Rotation angle of the insert
ϕ_S	: Immersion angle or swept angle of cut
ϕ_T	: Angle between teeth $(=2\pi/N)$
a	: Depth of cut in axial direction [mm]
$h(\phi)=S_t \sin\phi$	: Instantaneous uncut chip thickness at an angle ϕ
K_T	: Specific cutting coefficient [N/mm^2]
N	: Number of teeth
$r(h(\phi))$	: Tangential to radial cutting force ratio at an angle ϕ
$r(h(\phi_S))$	: Tangential to radial cutting force ratio at an immersion angle ϕ_S
S_t	: Feed per tooth [mm'/tooth]

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1. Introduction

Among the parameters for monitoring the cutting process, the cutting force signal is known to be the most accurate. When monitoring the cutting process by cutting force, a limit value is needed to separate abnormal state, such as tool breakage and overload, from normal state. This predetermined value is called threshold. Since threshold is a function of cutting parameters, identification of cutting parameters is necessary to set the threshold accurately. In the face milling process, radial depth of cut or radial immersion ratio is the parameter that affects the determination of the threshold most significantly. Therefore, estimation of immersion ratio is needed to adjust the threshold according to the cutting conditions.

Estimation of the cutting conditions during machining has been carried out. An algorithm to identify both axial depth and radial width of cut based on two orthogonal force measurements was developed (Altantis, 1987). Cubic polynomial was used to establish the immersion ratio prediction model. Another algorithm based on the mean and time varying components of the measured force was also developed (Altintas, 1989). They showed that the immersion ratio can be represented by the ratio of the mean squared value of instantaneous cutting force to the square of the quasi mean resultant force. The time during a tool was engaged with the workpiece was measured to estimate the immersion ratio using cutting force (Tarn, 1989). The trend of the cutting force variation was used to estimate the radial and axial immersion ratios (Choi, 1997). Both cutting force and tools engaging time in workpiece were used to identify immersion ratio even when more than two inserts were involved in cutting (Lee, 1998). The measured instantaneous and calculated average cutting forces at the swept angle of cut were used to identify the immersion ratio by iterative calculation (Hwang, 1999).

In this paper, an algorithm for on-line estimation of the radial immersion angle in the face milling is presented. When an insert finishes sweeping, a sudden drop of force occurs. The force drop is equal to the cutting force that acts on an insert at the swept angle of cut, and can be acquired from cutting force signals in feed and cross-feed directions. The force drop is also a function of the immersion angle and the ratio between tangential and radial direction force. If the tangential to radial force ratio is known, the immersion angle can be obtained from the measured cutting force. In this study, it is found that one preliminary experiment is enough to determine the tangential to radial force ratio, which can be used regardless of the cutting speed, axial depth of cut, feed rate, axial rake angle and number of teeth. Once the ratio is identified, immersion angle can be estimated from measured cutting force using iterative calculation. The experiments executed with different cutting conditions show that the proposed method works within 5% of error range.

2. Algorithm for Estimation of Radial Immersion Ratio

The tangential force, F_T and the radial force, F_R can be represented by instantaneous uncut chip thickness, $S_t \sin(\phi)$, depth of cut, a, specific cutting pressure, K_T, and the ratio between F_T and F_R.

$$F_T(\phi) = K_T a S_t \sin\phi \tag{1}$$

$$\begin{aligned} F_R(\phi) &= rF_T \\ &= r(h(\phi))K_T S_t \sin\phi \end{aligned} \tag{2}$$

The cutting forces in the feed direction, F_X, and the cross-feed direction, F_Y, on an insert at the swept angle of cut, ϕ_s, can be expressed as

$$\begin{aligned} F_X(\phi_s) &= F_T \cos\phi_s + F_R \sin\phi_s \\ &= K_T a S_t \sin\phi_s \cos\phi_s \\ &\quad + r(h(\phi_s))K_T a S_t \sin^2\phi_s \end{aligned} \tag{3}$$

$$\begin{aligned} F_Y(\phi_s) &= F_R \cos\phi_s - F_T \sin\phi_s \\ &= r(h(\phi_s))K_T a S_t \sin\phi_s \cos\phi_s \\ &\quad - K_T a S_t \sin^2\phi_s \end{aligned} \tag{4}$$

Cutting forces are the functions of the cutting condition such as the depth of cut, feed rate and radial immersion angle. The ratio of $F_Y(\phi_s)$ to $F_X(\phi_s)$ is a function of the swept angle of cut (or the immersion angle), ϕ_s, and the ratio of the tangential force to radial force, r.

$$\frac{F_Y(\phi_s)}{F_X(\phi_s)} = \frac{r(h(\phi_s)) - \tan(\phi_s)}{1 + r(h(\phi_s))\tan(\phi_s)} \tag{5}$$

The face milling is an intermittent process whose cutting force shows intermittent pattern as shown in Fig. 1. A sudden drop of cutting force occurs at the immersion angle because a tooth finished machining and is released from the work material. The amount of cutting force drop at the immersion angle during multi-tooth machining is calculated as follows.

$$\begin{aligned} dF_X(\phi_s) &= \sum_{i=1}^{N} F_{X_i}(\phi_s - (i-1)\phi_T) \\ &\quad - \sum_{i=2}^{N} F_{X_i}(\phi_s - (i-1)\phi_T) \end{aligned} \tag{6}$$

$$\begin{aligned} dF_Y(\phi_s) &= \sum_{i=1}^{N} F_{Y_i}(\phi_s - (i-1)\phi_T) \\ &\quad - \sum_{i=2}^{N} F_{Y_i}(\phi_s - (i-1)\phi_T) \end{aligned} \tag{7}$$

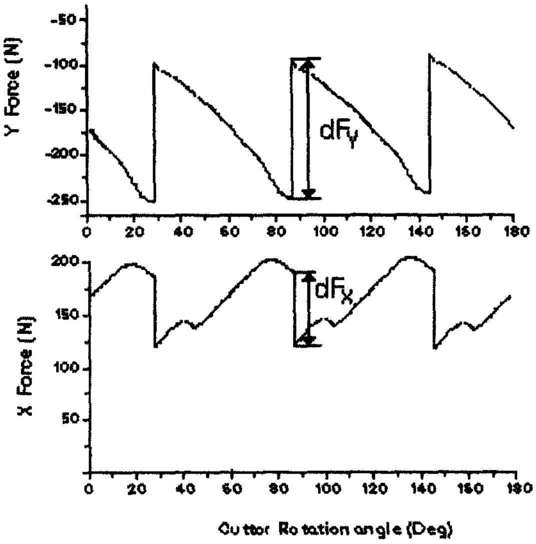

Fig. 1 Cutting force pattern when more than two teeth are involved in cutting

Combining Eq. (5), (6) and (7) yields,

$$\frac{dF_Y}{dF_X}=\frac{r(h(\phi_S))-\tan(\phi_S)}{1+r(h(\phi_S))\tan(\phi_S)} \tag{8}$$

Eq. (8) can be rewritten as,

$$\phi_S=\tan^{-1}\frac{r(h(\phi_S))-dF_Y/dF_X}{r(h(\phi_S))\cdot dF_Y/dF_X+1} \tag{9}$$

If the ratio between feed and cross-feed direction, $r(h(\phi_S))$, is determined as a function of ϕ_S, the immersion angle can be estimated from the measured feed and cross-feed direction cutting force using Eq. (9). The ratio, $r(h(\phi_S))$, is obtained from the preliminary experiment.

3. Experiments

3.1 Experimental set-up

A schematic representation of the experimental set-up is shown in Fig. 2. Experiments were carried out on a vertical machining center (Daewoo ACE-V500). The cutting force was measured by a piezo-type tool dynamometer (Kistler 9257B) and the measured force was amplified using a charge amplifier (Kistler 5011). Low pass filter in the charge amplifier with 300 Hz passing frequency was used to filter out the high frequency noise. The A/D converter (NI PCI-MIO-16E-4) and PC were used for data processing. Sampling of the force components was controlled by the signal from the encoder attached to the end of the spindle. In the experiments, 512 pulses per revolution were produced by the encoder. Face milling cutter with 125mm diameter was used to cut carbon steel SM45C(ANSI 1045) for single tooth machining, and the cutter with 100mm diameter was used to cut aluminum alloy 6061 for multi-tooth machining. The inserts were coated carbide grade (TaeguTec SEKN1203AFN P25 for single tooth machining and SDKN53MT KT750-10 for multi-tooth machining, respectively).

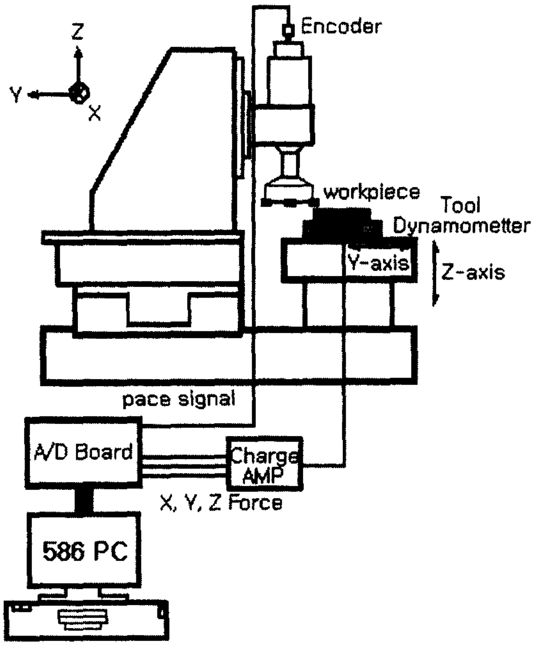

Fig. 2 Experimental set up

3.2 Experimental conditions

Cutting condition for single tooth machining is given in Table 1. Each of 3 cutting conditions (cutting speed, depth of cut, feed rate) varied while the remaining 2 cutting conditions were kept constant. In order to find the effect of the rake angles, another set of experiment for single tooth machining were carried out with a fixed 45 ° lead angle cutter, while the radial and axial rake angles varied from 0° to −10° and from 10° to 20°, respectively as listed in Tables 2 and 3.

Table 1 Cutting conditions for single tooth machining

	Cutter diameter (mm)	Spindle speed (RPM)	Axial depth of cut (mm)	Feed per tooth (mm/tooth)
Variation of the depth of cut	125	600	1.5	0.20
	125	600	2.0	0.20
	125	600	3.0	0.20
Variation of the spindle speed	125	540	2.0	0.20
	125	600	2.0	0.20
	125	720	2.0	0.20
	125	780	2.0	0.20
Variation of the feed per tooth	125	600	2.0	0.10
	125	600	2.0	0.12
	125	600	2.0	0.14
	125	600	2.0	0.16
	125	600	2.0	0.18
	125	600	2.0	0.20

Table 2 Variation of radial rake angle

Axial Rake Angle	20°					
Radial Rake Angle	0°	−2°	−4°	−6°	−8°	−10°

Table 3 Variation of axial rake angle

Radial Rake Angle	−6°					
Axial Rake Angle	10°	12°	14°	16°	18°	20°

Table 4 Cutting conditions for multi-tooth machining

		Cutter diameter (mm)	Spindle speed (RPM)	Axial depth of cut (mm)	Feed per tooth (mm/tooth)
Varying immersion ratio	Variation of the depth of cut	125	600	1.5	0.20
		125	600	2.0	0.20
		125	600	3.0	0.20
	Variation of the spindle speed	125	540	2.0	0.20
		125	600	2.0	0.20
		125	720	2.0	0.20
		125	780	2.0	0.20
	Variation of the feed per tooth	125	600	2.0	0.12
		125	600	2.0	0.14
		125	600	2.0	0.16
		125	600	2.0	0.18

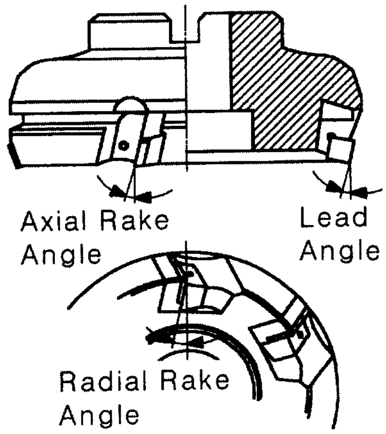

Fig. 3 Configuration of the facemill cutter

Cutting condition for multi-tooth machining is given in Table 4. The cutter had 45° lead angle, 12° axial rake angle, 7° radial rake angle and 5 of 45° chamfered inserts wese installed on the cutter for the experiments.

4. Results and Discussion

4.1 The dependency of the tangential to radial force ratio on the uncut chip thickness

The tangential to radial force ratio, r in Eq. (10) is a function of uncut chip thickness and obtained experimentally under the cutting condition with 600rpm cutting speed, 0.2mm/tooth and 2.0mm depth of cut. The ratio is decreased until the immersion angle reaches 90°, and increased again symmetrically as shown in Fig. 4. Therefore the ratio can be fitted using the following exponential equation.

$$\begin{aligned} r &= b_1 e^{b_2 h(\phi_s)} + b_2 \\ &= b_1 e^{b_2 S_t \sin\phi_s} + b_2 \end{aligned} \quad (10)$$

where b_1 and b_2 are constant.

4.2 The Independency of the tangential to radial force ratio of the cutting conditions

The effect of the cutting conditions on the tangential to radial force ratio is investigated. The cutting condition is given in Table 1, and the calculated ratio is given in Figs. 5~7, which

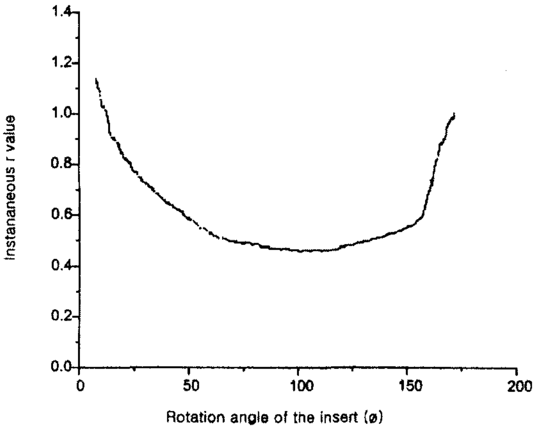

Fig. 4 Instantaneous r value at various rotation angle (single tooth, feed/tooth 0.2mm/tooth, spindle speed 600rpm, axial depth of cut 2.0mm)

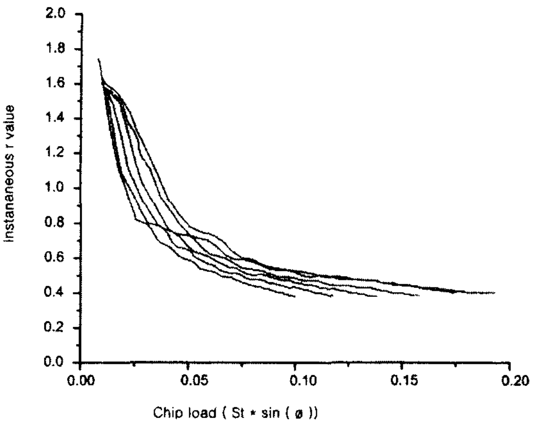

Fig. 5 Instantaneous r value with various feed/tooth (feed/tooth 0.1, 0.12, 0.14, 0.16, 0.18, 0.2mm/tooth, spindle speed 600rpm, axial depth of cut 1.0mm)

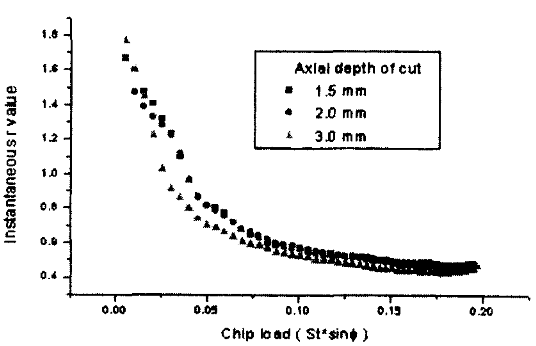

Fig. 6 Instantaneous r value with various axial depth of cut (feed per tooth 0.2mm/tooth, spindle speed 600rpm)

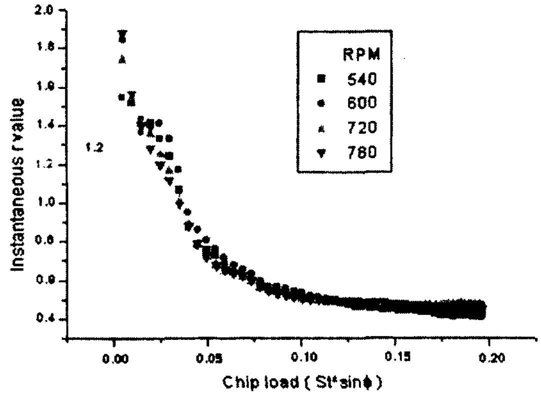

Fig. 7 Instantaneous r value with various spindle speed (feed per tooth 0.2mm/tooth, axial depth of cut 1.0mm)

show the effects of feed rate, axial depth of cut and cutting speed on the ratio, respectively. Since the ratio does not vary much according to the variation of the cutting conditions, it can be said that the ratio is independent of the cutting conditions.

Another experiments were executed to find the effect of the rake angles on the ratio. The variation of rake angles is given in Tables 2 and 3. The results in Figs. 8 and 9 show that the ratio is also independent of the axial rake angle but dependent on the radial rake angle. It attributes to the fact that the variation in the axial rake angle does not change the ratio between radial and tangentail force, while the variation in radial rake angle changes the ratio between radial and tangential force.

As a result, the tangential to radial force ratio is independent of the cutting speed, feed rate, axial depth of cut and axial rake angle, and dependent on radial rake angle and uncut chip thickness. Therefore, it is a reasonable assumption that the ratio can be fitted to Eq. (10) regardless of the cutting conditions.

Figure 10 shows the estimated immersion angle by the proposed method when the immersion angle is 78° during single tooth machining. Even though the equation about immersion angle ϕ is obtained from the experiment where the cutting condition is 0.2mm/tooth, 600rpm and 2.0mm depth of cut as shown in Fig. 4, it estimates the

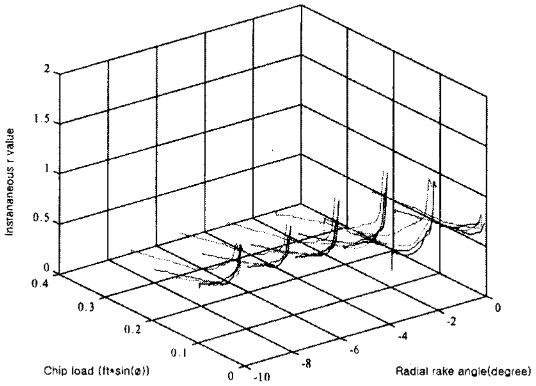

Fig. 8 Instantaneous r value with various radial rake angle
(radial rake angle 0°, −2°, −4°, −8°, −10°)

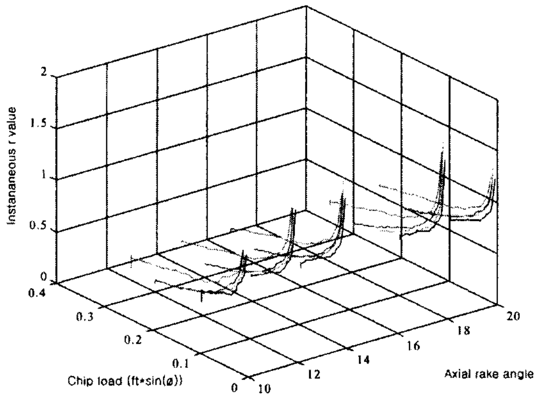

Fig. 9 Instantaneous r value with various axial rake angle
(axial rake angle 10°, 12°, 14°, 16°, 18°, 20°)

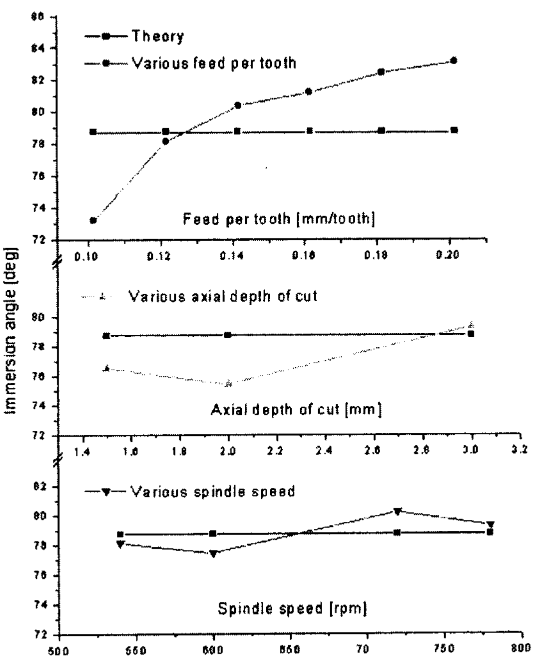

Fig. 10 Estimation of Immersion angle with various cutting conditions

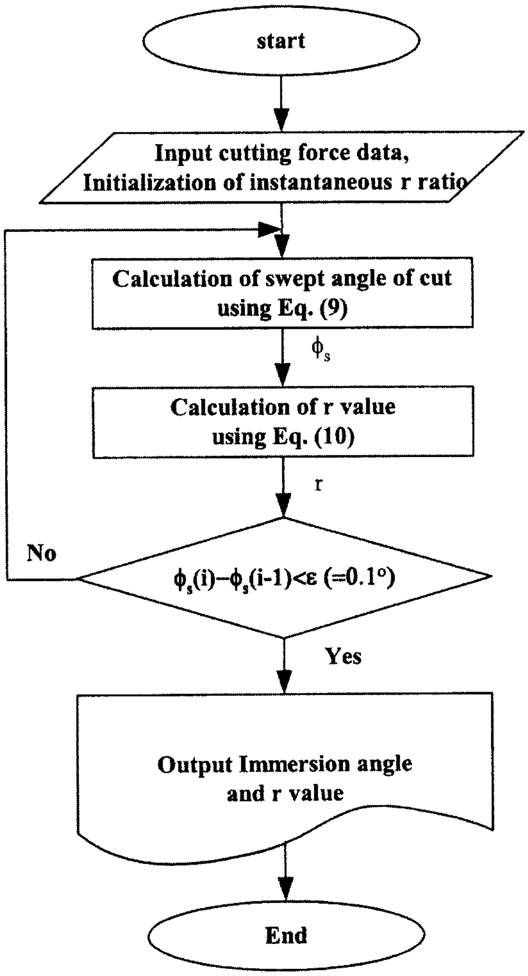

Fig. 11 Flow chart for the extimation of immersion angle

immersion angle within 5% error range for the experiments executed under different cutting conditions.

4.3 Immersion ratio estimation algorithm

The immersion ratio estimation algorithm is given in Fig. 11. First, the cutting force drop in feed and cross-feed direction at the swept angle of cut are measured, and the initial value of r is set arbitrarily between 0 and 1. Initial r value is inserted to the Eq. (9) to obtain the immersion angle, which is used to calculate r using Eq. (10). Newly obtained r is used to update the immersion angle. This iterative calculation is executed until the difference between new and old immersion angle is smaller than the preset error range, ε. In this work, ε is set to be 0.1°.

4.4 Convergence of the tangential to radial force ratio

In the previous section, r was calculated by iterative calculation. For the existence of the solution, difference between the derivatives of Eq. (9) and (10) must be either positive or negative in the range of all possible value of the ratio and immersion angle. Otherwise, the solutions for the ratio and the immersion angle will fluctuate so that they will not converge by iterative calculation. [6] The derivative of the immersion angle, Eq. (9), and the ratio, Eq. (10), about r is as follows.

$$\frac{d\phi_s}{dr}=\frac{1+2A\tan(\phi_S)-\tan^2(\phi_S)}{2A\tan(\phi_S)\sec^2(\phi_S)}+\frac{1+2A\tan(\phi_S)-\tan^2(\phi_S)}{B\cos(\phi_S)(1+\tan^2(\phi_S))}+\frac{(1+2A\tan(\phi_S)-\tan^2(\phi_S))^2}{2A(A\sec^2(\phi_S)+B\sin(\phi_S)-\tan(\phi_S)\sec^2(\phi_S))(1+\tan^2(\phi_S))} \quad (11)$$

$$\frac{d\phi_S}{dr}=\frac{1}{b_1b_2S_te^{b_2S_t\sin(\phi_S)}\cos(\phi_S)} \quad (12)$$

where, $A=b_2+b_1e^{b_2S_t\sin(\phi_S)}$, $B=b_1b_2S_te^{b_2S_t\sin(\phi_S)}$

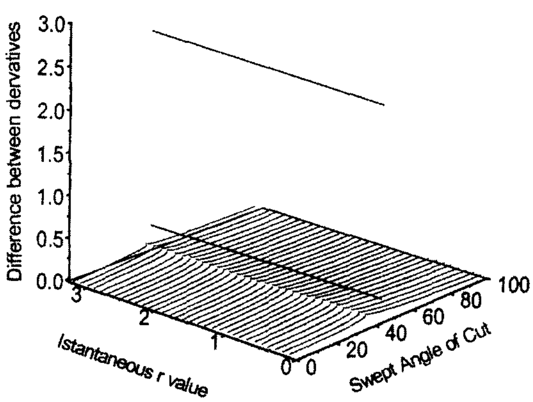

Fig. 12 Difference between derivatives of immersion angle calculated from instantaneous cutting forces and instantaneous cutting force ratio

The difference between Eqs. (11) and (12) is shown in Fig. 12 as a function of immersion angle and the tangential and radial force ratio. As shown in the figure, the difference is always positive which means that the solutions converge to a certain value in the range of possible value of the ratio and immersion angle.

4.5 Estimation of the ratio and the immersion ratio during multi-tooth machining

Experiments were carried out under various cutting conditions: various spindle speed, depth of cut, feed rate and with different workpiece material. These cutting conditions are given in Table 1, and the results are shown in Figs. 13~15. The estimated immersion angle is within 5%

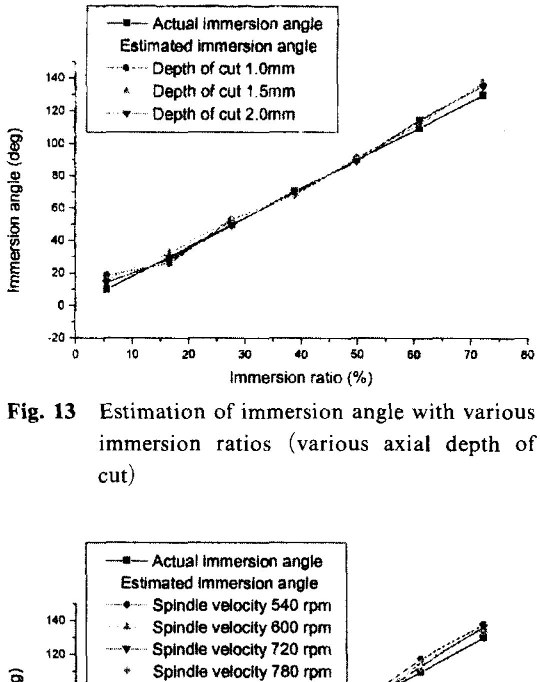

Fig. 13 Estimation of immersion angle with various immersion ratios (various axial depth of cut)

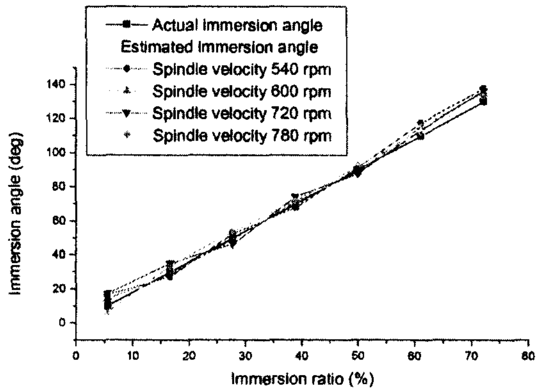

Fig. 14 Estimation of immersion angle with various immersion ratios (various spindle speed)

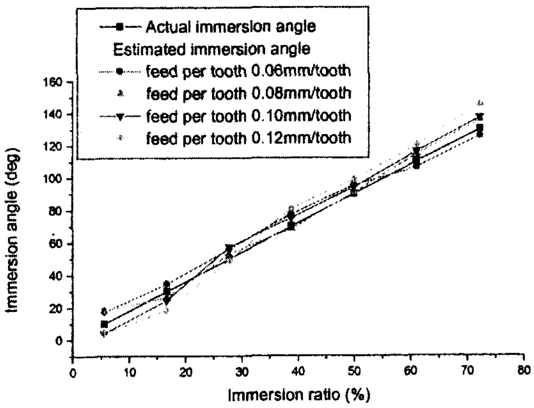

Fig. 15 Estimation of immersion angle with various immersion ratios (various feed per tooth)

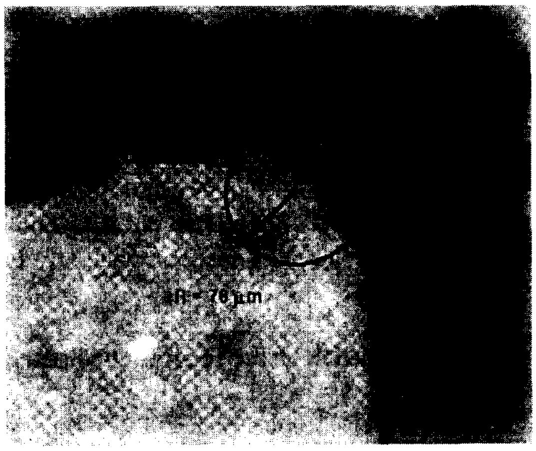

Fig. 17 Edge radius of insert

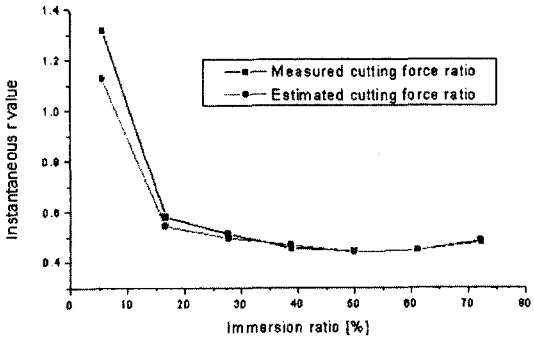

Fig. 16 Instantaneous r value (5 teeth, feed per tooth 0.2mm/tooth, axial depth of cut 1.0mm, spindle speed 600rpm)

error range regardless of the cutting conditions. Figure 16 shows the estimation results of the tangential to radial force ratio with 0.2mm/tooth, 1.0mm axial depth of cut, 600rpm spindle speed during multi-tooth machining. The cutter with 100mm diameter was used for the experiment. Compared with other tangential to radial force ratio, the error is relatively large when r is small. It is attributed to the edge effect or parasitic force. The measured edge radius of insert was 70-80μm, even though the insert was a brand new tool. The cutting force is assumed to be linear to the feed per tooth in Eqs. (1) and (2). Because of the dull part at the end of the insert, the cutting force is not proportional to the feed per tooth when feed per tooth is small, which causes the discrepancy between the calculated and measured cutting force. The discrepancy grows larger as the feed per tooth becomes smaller. As a result, the error of the estimated immersion ratio based on larger linear cutting force with smaller feed per tooth, which explains the reason of relatively big error of tangential and radial force ratio and immersion ratio with small immersion angle. Figure 17 shows the measured edge radius of the insert, whose radius is about 78μm.

5. Conclusions

The force drop at the immersion angle is used to determine the force applied on an insert in feed and cross-feed direction. The ratio between the feed and cross-feed direction forces is also expressed as a function of immersion angle and the ratio between tangential and radial direction force. The relation between the tangential to radial force ratio is independent of cutting speed, depth of cut, feed rate, axial depth of cut. It only depends on radial rake angle, tool and workpiece material. Only one experiment is needed to determine the relation between the tangential to radial force ratio and immersion angle with given tool and workpiece material.

Iterative calculation is used to solve the problem. Proposed algorithm works well within 5% error range regardless of cutting conditions: cutting speed, depth of cut, feed per tooth, cutter diameter, number of inserts. The relatively large estimation error with small immersion ratio is attributed to the edge effect or parasitic force at the end of the insert.

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