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Radial immersion angle estimation using cutting force and predetermined cutting force ratio in face milling

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Abstract

Radial immersion ratio is an important factor to determine the threshold for tool conditioning monitoring and automatic force regulation in face milling. In this paper, a method of on-line estimation of the radial immersion angle using cutting force is presented. When a tooth finishes sweeping, a sudden drop of cutting force occurs. This force drop is equal to the cutting force that acts on a single tooth at the swept angle of cut and can be obtained from the cutting force signal in feed and cross-feed directions. 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. In this study, it is found that the ratio of radial-to-tangential cutting force is not affected by cutting conditions and axial rake angle. Therefore, the ratio of radial-to-tangential cutting force determined by just 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 a predetermined ratio, the radial immersion ratio is estimated in the process. Various experiments show that the radial immersion ratio and instantaneous ratio of the radial to tangential direction cutting force can be estimated very well by the proposed method.

Keywords: Radial immersion ratio; Cutting force ratio; Cutting force; Estimation

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, there needs to be a limiting value to separate abnormal states, such as tool breakage and overload, from normal states. This predetermined value is called the threshold. Since the threshold is a function of the 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 most affects the determination of the threshold. 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 in the past. Altintas and Yellowley [1] developed an algorithm to identify both axial depth and radial width of cut based on two orthogonal force measurements. The cubic polynomial was used to establish the immersion ratio prediction model. Altintas and Yellowley [2] also developed another algorithm based on the mean and time-varying components of the measured force. They showed that the immersion ratio can be represented by the ratio of the mean squared value of the instantaneous cutting force to the square of the quasi-mean resultant force. Tarn and Tomizuka [3] measure the time during which a tool is engaged with the workpiece to estimate the immersion ratio using cutting force. Choi and Yang [4] used the trend of the cutting force variation to estimate the radial and axial immersion ratios. Lee [5] used both cutting force and tool-engaging time with the workpiece to identify the immersion ratio even when more than two inserts are involved in cutting. Hwang [6] used the measured instantaneous and calculated average cutting forces at the swept angle of cut to identify the immersion ratio by iterative calculation.

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In this paper, an algorithm for on-line estimation of the radial immersion angle in 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 just one preliminary experiment is enough to determine the tangential-to-radial force ratio, which can be used regardless of cutting speed, axial depth of cut, feed rate, axial rake angle, and number of teeth. Once the ratio is identified, the immersion angle can be estimated from the measured cutting force using iterative calculation. The experiments executed with different cutting conditions show that the proposed method works within 5% of the 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 $\sin(\phi)$, immersion angle, ϕ, depth of cut, α, specific cutting pressure, K_T, and the ratio, r, between F_T and F_R. [2]

$$F_T(\phi) = \mathrm{K}_T a S_t \sin(\phi), \tag{1}$$

$$F_R(\phi) = rF_R = r(h(\phi))K_T S_t \sin(\phi). \tag{2}$$

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

$$F_X(\phi) = F_T\cos(\phi) + F_R\sin(\phi) \tag{3}$$
$$= K_T a S_t \sin(\phi)\cos(\phi) + r(h(\phi))K_T a S_t \sin^2(\phi),$$

$$F_Y(\phi) = F_R\cos(\phi) - F_T\sin(\phi) \tag{4}$$
$$= r(h(\phi))K_T a S_t \sin(\phi)\cos(\phi) - K_T a S_t \sin^2(\phi).$$

Cutting forces, F_x and F_Y, are functions of cutting conditions such as depth of cut, feed rate, and radial immersion angle. The ratio of F_Y (ϕ_s) to F_x (ϕ_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:

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

Face milling is an intermittent process where the cutting force shows an intermittent pattern. A sudden drop of cutting force occurs at the immersion angle because a tooth finishes 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:

$$dF_X(\phi_s) = \sum_{i=1}^{N} F_{X_i}(\phi_s - (i-1)\phi_T) - \sum_{i=2}^{N} F_{X_i}(\phi_s - (i-1)\phi_T), \tag{6}$$

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

where ϕ_T is the angle between the teeth. A combination of Eqs. (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

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

If the ratio between feed and cross-feed directions, $r(h(\phi_s))$, 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 and results

3.1. Experimental set-up

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

The cutting condition for single-tooth machining is given in Table 1. Each of the three cutting conditions (cutting speed, depth of cut, feed rate) varies while the remaining two cutting conditions are kept constant. To

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

find the effect of the rake angles, another set of experiments for single-tooth machining are carried out with a fixed 45° lead angle cutter, while the radial rake angle and the axial rake angle varied from 0° to –10° and from 10° to 20°, respectively.

The cutting condition for multi-tooth machining is given in Table 2. The cutter has 45° lead angle, 12° axial rake angle, 7° radial rake angle, and 5 of 45° chamfered inserts are installed on the cutter for the experiments.

3.2. The dependency of the tangential-to-radial force ratio on the uncut chip thickness

The tangential-to-radial force ratio, ϕ_s in Eq. (9) is a function of uncut chip thickness and is obtained experimentally under the cutting condition with 600 rpm cutting speed, 0.2 mm/tooth feed/tooth and 2.0 mm depth of cut. The ratio is decreased until the immersion angle reaches 90° and increased again symmetrically. The ratio, therefore, can be fitted by the following exponential equation

$$r = b_1 e^{b_2 h(\phi_s)} + b_3 = b_1 e^{b_2 s_t \sin(\phi_s)} + b_3 \quad (10)$$

where b_1, b_2, and b_3 are constant.

3.3. The independence 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 in this section. The cutting condition is given in Table 1 and the calculated ratio is given in Figs. 1–3, each of which shows the effect of feed rate, axial depth of cut, and cutting speed on the ratio, respectively. The ratio does not vary much according to the variation of the cutting conditions and it can be said that the ratio is independent of the cutting conditions. Another experiment was executed to find the effect of the rake angle on the ratio. The results in Figs. 4 and 5 show that the ratio is also independent of the axial rake angle but dependent on the radial rake angle. As a result, the tangential-to-radial force ratio is independent of the cutting speed, feed rate, axial depth of

Table 2
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	100	600	1.5	0.2
		100	600	2.0	0.2
		100	600	3.0	0.2
	Variation of the spindle speed	100	540	2.0	0.2
		100	600	2.0	0.2
		100	720	2.0	0.2
		100	780	2.0	0.2
	Variation of the feed per tooth	100	600	1.0	0.06
		100	600	1.0	0.08
		100	600	1.0	0.10
		100	600	1.0	0.112

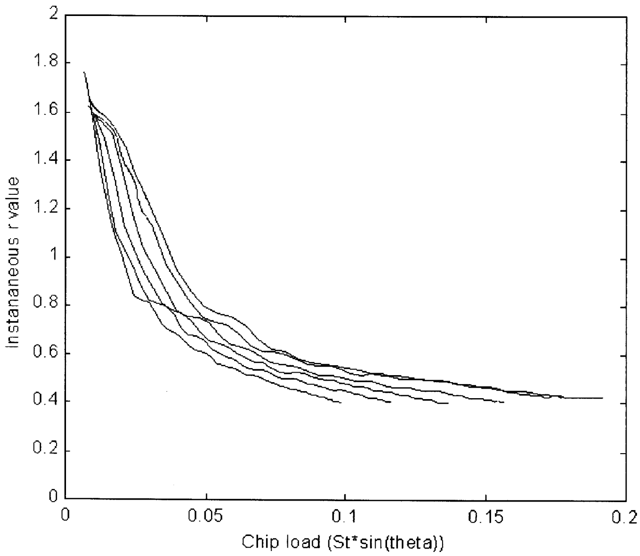

Fig. 1. Instantaneous *r* value with various feeds per tooth (feed/tooth 0.1, 0.12, 0.14, 0.16, 0.18, 0.2 mm/tooth, spindle speed 600 rpm, axial depth of cut 1.0 mm).

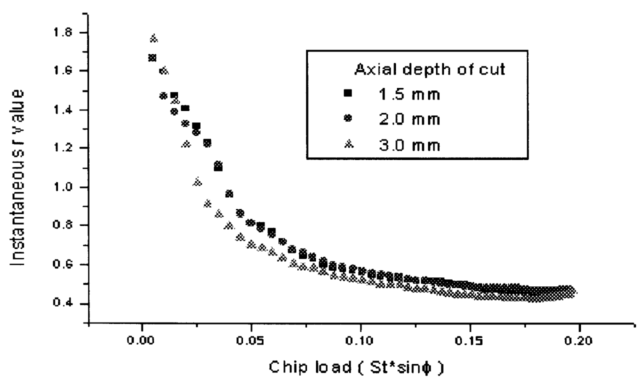

Fig. 2. Instantaneous *r* value with various axial depths of cut (feed/tooth 0.2 mm/tooth, spindle speed 600 rpm).

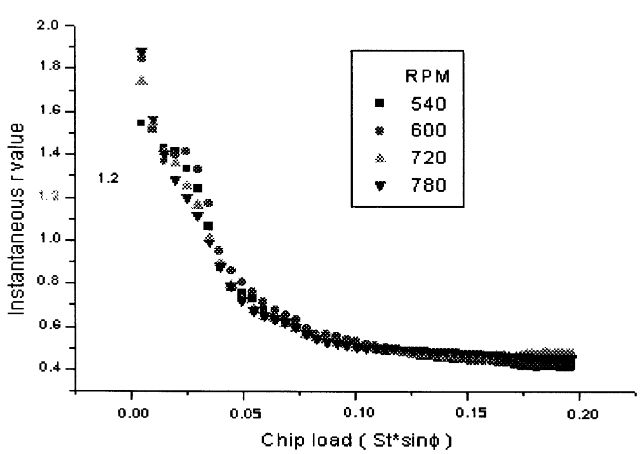

Fig. 3. Instantaneous *r* value with various spindle speeds (feed/tooth 0.2 mm/tooth, axial depth of cut 1.0 mm).

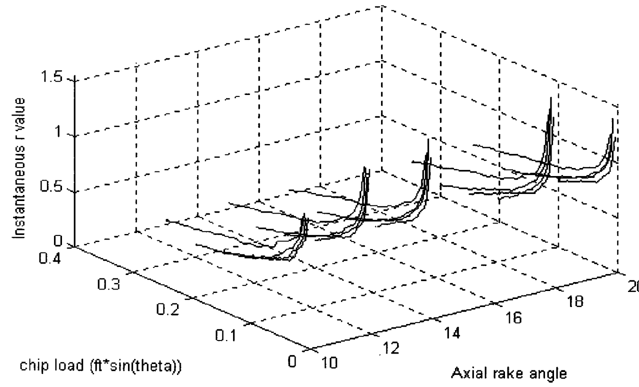

Fig. 4. Instantaneous *r* value with various rake angles (radial rake angle 0°, –2°, –4°, –6°, –8°, –10°).

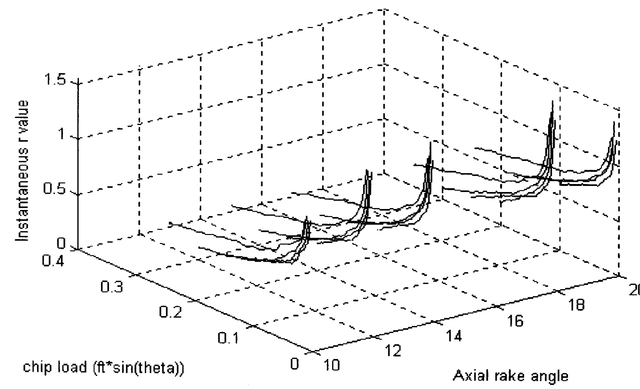

Fig. 5. Instantaneous *r* value with various rake angles (axial rake angle 10°, 12°, 14°, 16°, 18°, 20°).

cut, and axial rake angle and dependent on radial rake angle and uncut chip thickness. So it is a reasonable assumption that the ratio can be fitted to Eq. (10) regardless of the cutting conditions. Fig. 6 shows the estimated immersion angle by the proposed method when the immersion angle is 78° during single-tooth machining. Even though the equation r about immersion angle ϕ was obtained from the experiment where the cutting condition is 0.2 mm/tooth, 600 rpm and 2.0 mm depth of cut, it estimated the immersion angle within 5% error range for the experiments executed under different cutting conditions.

3.4. Immersion ratio estimation algorithm

Iterative calculation method is used for estimating the immersion angle. First, the cutting force drop in feed and cross-feed directions at the swept angle of cut are measured and the initial value of r is set arbitrarily between 0 and 1. The initial r value is inserted in Eq. (9) to obtain the immersion angle, which is used to calculate r using Eq. (10). The newly obtained r is inserted into Eq. (9) to obtain the new immersion angle, again. This iterative calculation is executed until the difference

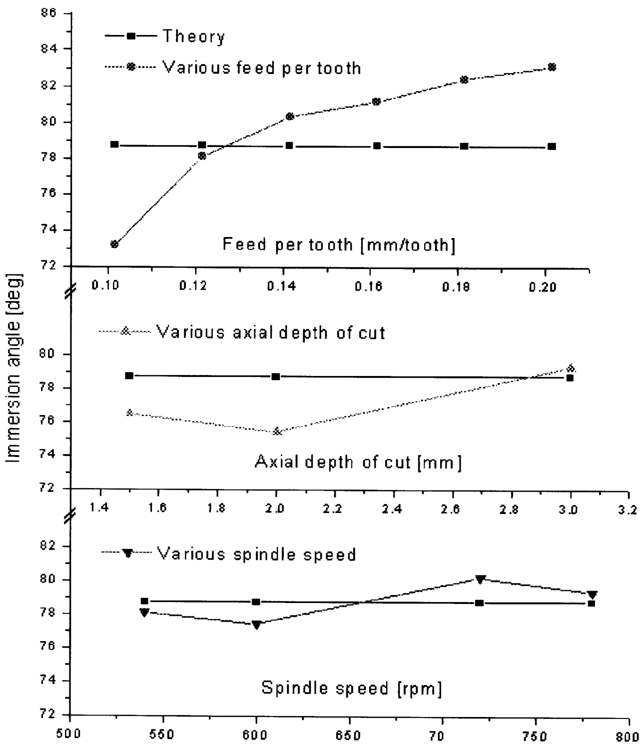

Fig. 6. Estimation of immersion angle with various cutting conditions.

between the new and old immersion angle is smaller than the preset error range, ε.

3.5. Convergence of the tangential-to-radial force ratio

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

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

$$+ \frac{(1 + 2A\tan(\phi_s) - \tan^2(\phi_s))^2}{2A(A\sec^2(\phi_s) + B\sin(\phi_s) - \tan(\phi_s)\sec^2(\phi_s))(1 + \tan^2(\phi_s))},$$

$$\frac{d\phi_s}{dr} = \frac{1}{b_1 b_2 S_t e^{b_2 S_t \sin(\phi_s)} \cos(\phi_s)} \quad (12)$$

where, $A = b_3 + b_1 e^{b_2 S_t \sin(\phi_s)}$, $B = b_1 b_2 S_t e^{b_2 S_t \sin(\phi_s)}$. The difference between Eqs. (11) and (12) is shown in Fig. 7 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

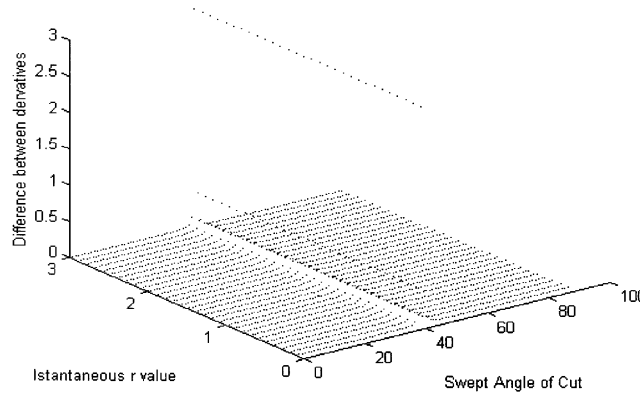

Fig. 7. Differnce between derivatives of immersion angle calculated from instantaneous cutting forces and instantaneous cutting force.

converge to a certain value in the range of possible values of the ratio and immersion angle.

3.6. Estimation of the ratio and the immersion ratio during multi-tooth machining

Experiments are carried out under various cutting conditions: various spindle speeds, depth of cut, feed rates, and with different workpiece materials. These cutting conditions are given in Table 1 and the results are shown in Figs. 8–10. The estimated immersion angle is within 5% of theerror range regardless of the cutting conditions. Fig. 11 shows the estimation results of the tangential-to-radial force ratio with 0.2 mm/tooth, 1.0 mm axial depth of cut, 600 rpm spindle speed during multi-tooth machining. The cutter with 100 mm diameter was used for the experiment. Compared with other tangential-to-radial force ratios, the error is relatively large when r is small. This is attributed to the edge effect or parasitic force.[2] The measured edge radius of the insert was 70–80 μm even though the insert was a brand new tool. The cutting

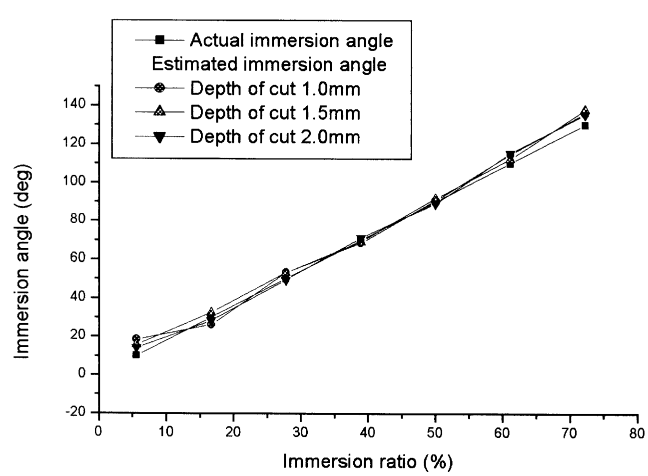

Fig. 8. Estimation of immersion angle with various immersion ratios (various depths of cut).

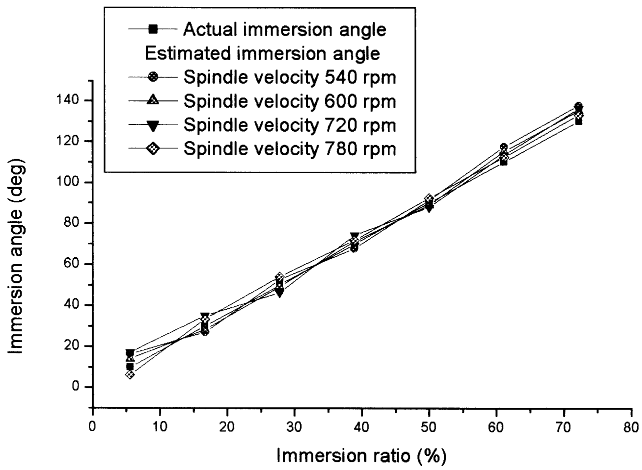

Fig. 9. Estimation of immersion angle with various immersion ratios (various spindle speeds).

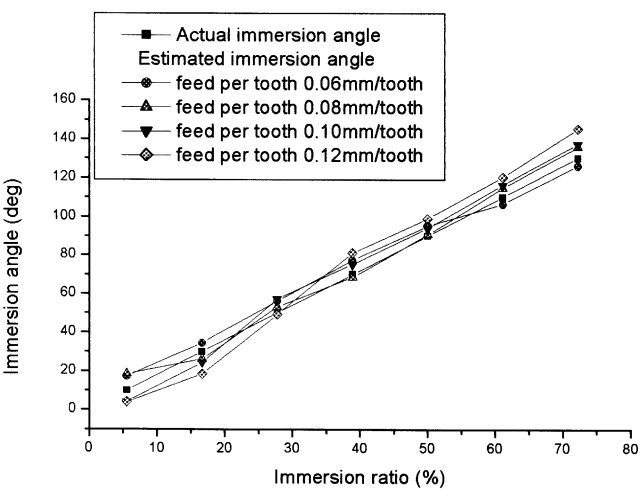

Fig. 10. Estimation of immersion angle with various immersion ratios (various feeds per tooth).

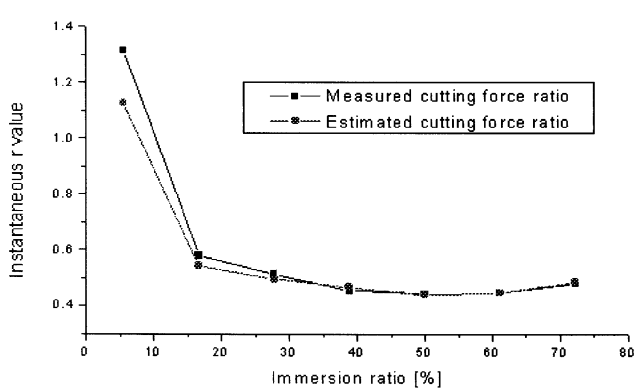

Fig. 11. Instantaneous r value (5 teeth, feed per tooth 0.2 mm/tooth, axial depth of cut 1.0 mm, spindle speed 600 rpm).

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 the feed per tooth is small, which causes the discrepancy between the calculated and measured cutting force. The discrepancy is bigger as the feed per tooth is smaller. As a result, the error of the estimated immersion ratio based on the linear cutting force is bigger as the feed per tooth is smaller, which explains the relatively large error of tangential and radial force ratios and immersion ratio with a small immersion angle. Fig. 12 shows the measured edge radius of the insert, whose radius is about 78 μm.

4. Conclusions

The force drop at the immersion angle is used to determine the force applied on an insert in feed and cross-feed directions. The ratio between the feed and cross-feed direction forces is also expressed as a function of the immersion angle and the ratio between the tangential and radial direction force. The relation between the tangential-to-radial force ratio is independent of cutting speed, depth of cut, feed rate, and axial depth of cut. It only depends on the radial rake angle and tool and workpiece material. Only one experiment is needed to determine the relation between the tangential-to-radial force ratio and immersion angle with a given tool and workpiece material.Iterative calculation is used to solve the problem that is unsolvable by analytical method. The proposed algorithm works well within 5% error range regardless of cutting conditions: cutting speed, depth of cut, feed per tooth, cutter diameter, or number of inserts. The relatively large estimation error when the immersion ratio is small is attributed to the edge effect or parasitic force at the end of the insert.

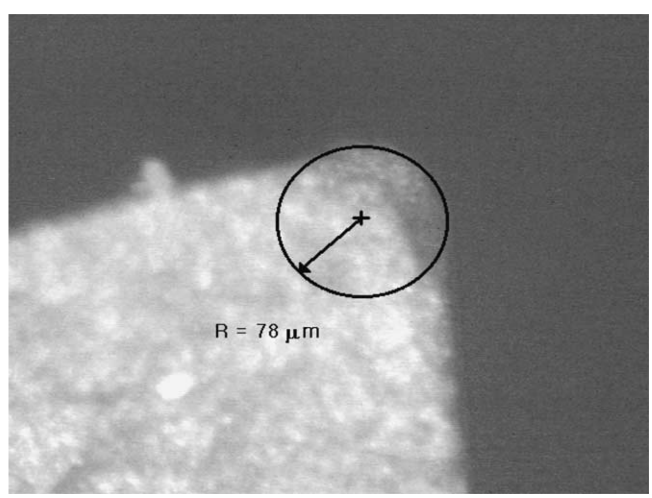

Fig. 12. Edge radius of an insert.

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