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Effects of shaft angle on cutting tool parameters in internal gear skiving †

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Abstract

Gear skiving has received considerable attention because of its high productivity, particularly in internal gear cutting, and skiving cutter design methods have been widely investigated. At the beginning of a cutter design process, a shaft angle, a center distance, and the number of teeth are examined as basic parameters for cutting gears. In current gear skiving, a shaft angle is generally set to be approximately 20°; however, the reason for selecting this value has not been clarified. In the present study, the validity of the value of shaft angle is discussed by calculating the cutting tool parameters, such as instantaneous rake angles, clearance angles, cut depths, and cutting speeds at continuously moving cutting points against various shaft angles. Therefore, the widely used value of shaft angle would result in moderate cutting tool parameters. In addition, the cutting force and cutter wear would be low when a cutter axis inclines opposite to the gear helix to be cut.

Keywords: Cutting tool parameter; Gear skiving; Internal gear; Opposite direction; Shaft angle

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1. Introduction

In recent years, the number of shift stages in automatic transmissions for automobiles has increased to reduce fuel consumption [1, 2]. In addition, high-precision gears have been required to enable highly efficient power transmissions [3]. For these purposes, gear accuracy should be improved to facilitate the completion of external gears through grinding and/or honing. However, few internal gears are finished after heat treatment because most internal gears have thin rims that cause large gear tooth deformations during operation, thereby reducing the motivation to improve accuracy. Therefore, tooth flank modifications have been rarely applied although they are assumed to work well. However, considerable accurate internal gears have been required for complicated and varied automotive transmissions. Gear skiving is used as a method to meet the requirements of producing accurate internal gears [4]. The principle of gear skiving was proposed more than 100 years ago in Germany [5]. However, this principle was not utilized as a major cutting method in gear manufacturing due to short tool life. Nevertheless, recent technologies, such as advanced numerical control and/or highly rigid machine tools, have improved tool life, and gear skiving can become a general gear cutting method. Gear skiving has attracted considerable attention and has been widely investigated; skiving cutters have been designed based on such studies [6, 7]. However, optimum design methods for skiving cutters have not been established yet. The design methods for skiving cutters should be constructed to prolong tool life and increase cutting efficiency.

The present study only considers taper-shaped cutters, which are commonly used in gear skiving. In this case, the number of teeth of a cutter, the center distance, and the shaft angle are used as the basic parameters for gear skiving. Experiments show that large shaft angles result in low cutting forces in gear skiving. Meanwhile, large shaft angles lead to interferences between cutters (or cutter holders) and gears. Therefore, a shaft angle is generally set to be approximately 20° and its direction is determined to reduce the helix angle of a cutter while avoiding such interferences. This condition is due to the reduction of tooth flank deviations of skived gears caused by the small helix angles of skiving cutters despite resharpening of tool faces.

In this work, the validity of the generally used value of shaft angle is examined by calculating the cutting tool parameters against various shaft angles. In addition, a cutter with a large helix angle, which is against the normal principle, is tested to confirm its potential.

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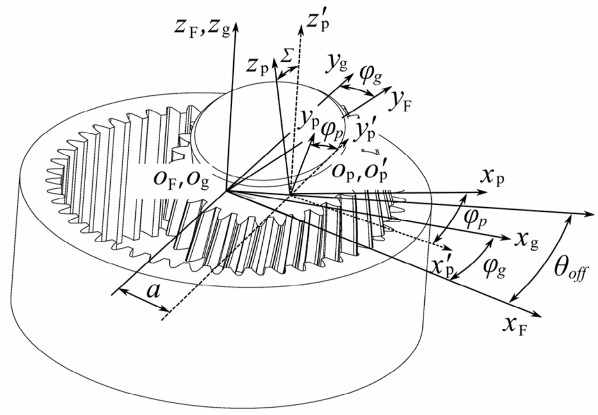


Fig. 1. Coordinate systems with an offset angle.

2. Summary of calculation

2.1 Coordinate systems

Fig. 1 shows the three established coordinate systems. $S_g(O_g\text{-}x_g, y_g, z_g)$, $S_p(O_p\text{-}x_p, y_p, z_p)$ and $S_F(O_F\text{-}x_F, y_F, z_F)$ are rigidly connected to a gear, a cutter, and a frame, respectively. $S'_p(O'_p\text{-}x'_p, y'_p, z'_p)$ is a system obtained by translating the origin O_F to the cutter origin O_p. The gear and cutter rotate around z_g and z_p, respectively. The relationship of gear rotation angle φ_g and cutter rotation angle φ_p is represented by

$$u = \phi_g / \phi_p \, , \tag{1}$$

where u is the gear-to-cutter ratio.

When φ_g and φ_p are zero, the directions of x_F and x_g, y_F and y_g, x_F and x_p and y_F and y_p are identical. Origin O_p is represented as (a, a tan(θ_{off}), 0), where a is the minimum distance between the gear axis z_g and cutter axis z_p. In this study, the cutter origin is (a, 0, 0), considering only taper-shaped cutters at zero of θ_{off}.

2.2 Cutter design

2.2.1 Cutting edge

A cutting edge is obtained as the intersection curve of a tool face with barrel-shaped pinion tooth flanks conjugated to gear tooth flanks (Fig. 2). The equation of meshing derived by Litvin, which is known as the necessary condition of envelope existence, provides the pinion flanks [8]. The position vectors of the points on gear tooth flanks and normal vectors to the flanks of each point are provided. By applying the equation of meshing to each point, the pinion tooth flanks are obtained as a set of points. In the present study, the cutting edge resulting from an obtained surface intersection curve is represented by Lagrange polynomials using two parameters and a tool face.

2.2.2 Helix angle

Generally, the shaft angle between the gear and cutter axis is set approximately from 10° to 30°. The difference between the shaft and helix angles of the gear produces the helix angle of a cutter. The directions of cutter axis and gear helix are generally on the same side (Fig. 3).

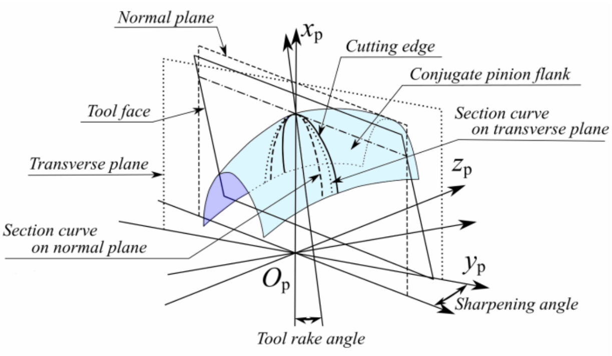


Fig. 2. Calculation concept of a cutting edge on a barrel-shaped pinion conjugated to a gear tooth flank.

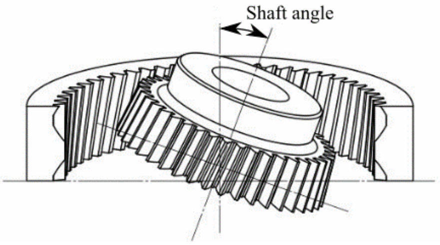


Fig. 3. Generally used setting for internal gear skiving.

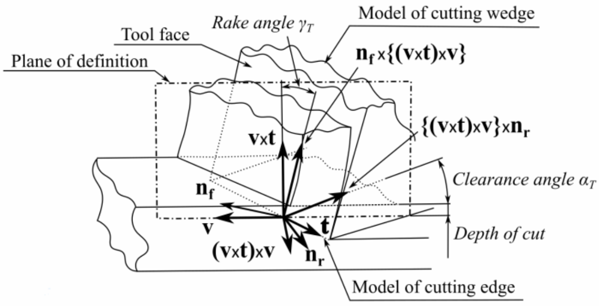


Fig. 4. Oblique cutting model for defining cutting tool parameters.

2.3 Calculation method for cutting tool parameters

Moriwaki et al. developed a calculation method for cutting tool parameters, which vary during the cutting motion of cylindrical skiving cutters [9]. Those parameters comprise cutting speeds, depths of cut, rake angles, and clearance angles. The calculation method simulates such cutting tool parameters in a cutting motion. Fig. 4 shows the definitions of depth of cut, rake angle, and clearance angle. The depth of cut is the length between the cutting point and surface generated by the previous cut in the direction of vector **v** × **t**. The rake and clearance angles are obtained as follows:

$$\gamma_T = \cos^{-1}\left[\frac{\mathbf{v}\cdot\left[\mathbf{n_f}\times\left\{(\mathbf{v}\times\mathbf{t})\times\mathbf{v}\right\}\right]}{\mathbf{v}\cdot\left|\mathbf{n_f}\times\left\{(\mathbf{v}\times\mathbf{t})\times\mathbf{v}\right\}\right|}\right]-\frac{\pi}{2}, \tag{2}$$

$$\alpha_T = \frac{\pi}{2}-\cos^{-1}\left[\frac{(\mathbf{v}\times\mathbf{t})\cdot\left[\left\{(\mathbf{v}\times\mathbf{t})\times\mathbf{v}\right\}\times\mathbf{n_t}\right]}{|\mathbf{v}\times\mathbf{t}|\cdot\left[\left\{(\mathbf{v}\times\mathbf{t})\times\mathbf{v}\right\}\times\mathbf{n_t}\right]}\right]. \tag{3}$$

3. Generally used setting

A shaft angle is generally determined to incline the cutter axis to the same side of the gear helix. Cutters with small helix angles are preferred [10] because they provide small profile deviations for skived gears after re-sharpening. The effects of shaft angles on cutting tool parameters are determined in this study.

3.1 Gear data

Gear data are listed in Table 1. The helix angle is set at 15° (LH) and the normal module at 2.0 mm.

Table 1. Gear data.

	Gear
Normal module	2.0
Number of teeth	60
Normal pressure angle (deg.)	20.0
Helix angle (deg.)	15(LH)
Tip diameter (mm)	120.0
Reference diameter (mm)	124.233
Root diameter (mm)	129.0
Base diameter (mm)	116.254
Prof. shift coefficient	0.0

3.2 Cutter data evaluation

The data for three types of cutters are listed in Table 2. The effects of shaft angles on cutting tool parameters are examined, and each cutter has different helix angles. Cutter nos. 01, 02 and 03 provide shaft angles of 10°, 20° and 30°, respectively. Those helix angles are 5° (LH), 5° (RH) and 15° (RH), respectively, and the gear helix angle is 15° (LH), as shown in Table 1.

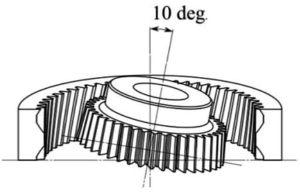
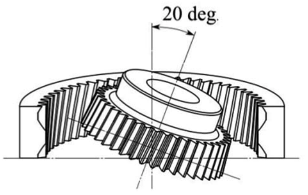
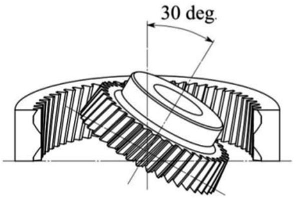
Schematic of a cutter mating with a gear in Table 2 shows the directions of cutter axes and shaft angle values. The cutter axes and gear helixes are on the same side for all cases. Such settings (Table 2) are generally preferred as described above.

3.3 Cutting tool parameters

Figs. 5-8 show the rolled-out chip forms without considering any deformations according to cutting edge motions. The solid blue line in Fig. 5(a) represents the feed mark, which is calculated as a trace of the initial cutting that appears on the gear tooth flank. The cutting edge moves downward from the line in this case. Other information shown in Fig. 5 is the distributions of cutting speeds. From the figure, a large shaft angle results in high cutting speed. Low cutting speed generally results in slight tool wear [11]; thus, the shaft angle of 10° provides the best cutting speed result among these shaft angles.

Fig. 6 shows the distributions of depths of cut. A large shaft angle results in small depths of cut. Generally, small depth of cut results in low cutting resistance [12]. Therefore, the shaft angle of 30° provides the best depth of cut among these shaft

Table 2. Data of three cutters.

	Cutter 04					
	Left flank	Right flank	Left flank	Right flank	Left flank	Right flank
Normal module	2.0		2.0		2.0	
Number of teeth	40		40		40	
Normal pressure angle (deg.)	20.0		20.0		20.0	
Helix angle (deg.)	5(LH)		5(RH)		15(RH)	
Helix angle (deg.)	2(LH)	8(LH)	8(RH)	2(RH)	18(RH)	12(RH)
Tip diameter (mm)	84.8		85.573		88.8	
Reference diameter (mm)	80.306		80.306		82.209	
Transverse pressure angle (deg.)	20.435	20.550	20.527	20.446	20.850	20.582
Base diameter (mm)	75.252	75.196	75.159	75.244	76.826	76.962
Side relief angle (deg.)	3.0		3.0		3.0	
Front relief angle (deg.)	6.7		7.3		8.4	
Rake angle (deg.)	10.0		10.0		10.0	
Sharpening angle (deg.)	5.0		5.0		15.0	
Shaft angle (deg.)	10		20		30	
Schematic diagram of cutter mating gear						

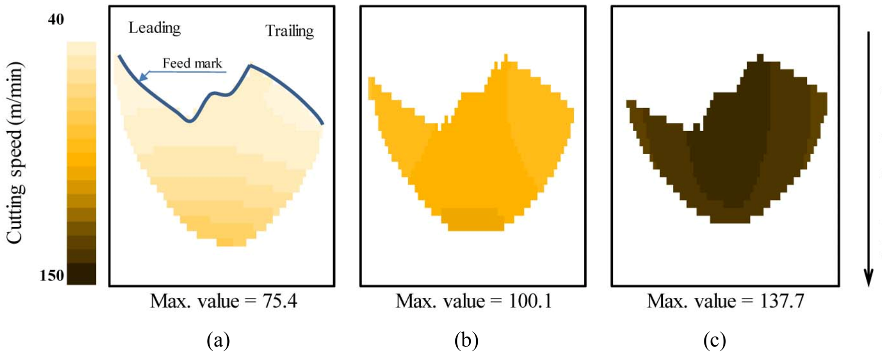


Fig. 5. Comparison of cutting speed: Shaft angle of (a) 10°; (b) 20°; (c) 30°.

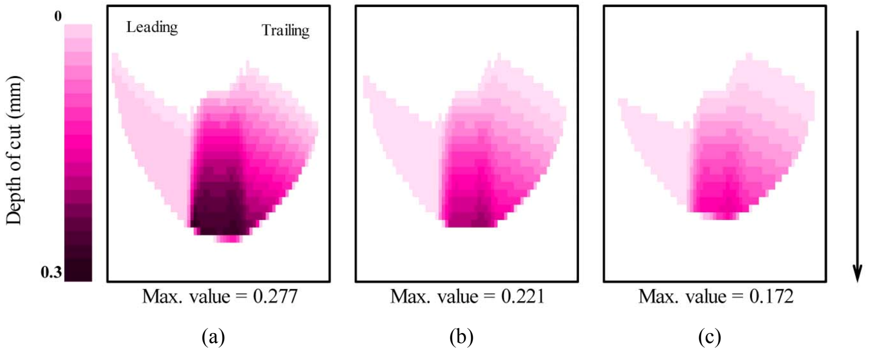


Fig. 6. Comparison of cut depth: Shaft angle of (a) 10°; (b) 20°; (c) 30°.

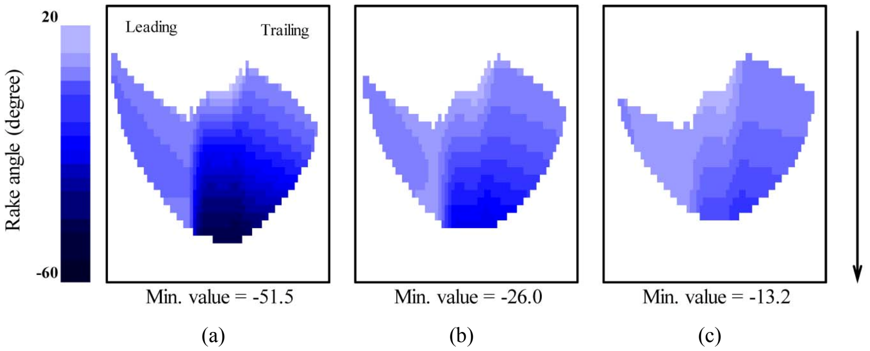


Fig. 7. Comparison of rake angle: Shaft angle of (a) 10°; (b) 20°; (c) 30°.

angles.

Fig. 7 shows the distributions of rake angles. A large negative rake angle in cutting motion is one of the features of gear skiving. Large shaft angles lead to small negative rake angles. Generally, large negative rake angles result in significant tool wear [12]. Thus, the shaft angle of 30° provides the best result for rake angle among these shaft angles.

Fig. 8 shows the distributions of clearance angles. A large clearance angle results in slight tool wear. All shaft angles provide similar minimum clearance angles.

Comparing the cutting forces of each setting is not easy because all parameters change as cutting edge advances. The cutting forces are calculated in this study using the following equations as indexes:

$$cutting\ force\ index = v^{n_v} \cdot d_e^{\,n_d} \cdot \gamma_T^{\,n_{Rk}} \cdot \alpha_T^{\,n_{cl}} , \quad (4)$$

$$v = \left(v - v_{\min}\right) / \left(v_{\max} - v_{\min}\right) , \quad (5)$$

$$d_e = \left(d_e - d_{e\min}\right) / \left(d_{e\max} - d_{e\min}\right) , \quad (6)$$

$$\gamma_T = \left(\gamma_T - \gamma_{T\min}\right) / \left(\gamma_{T\max} - \gamma_{T\min}\right) , \quad (7)$$

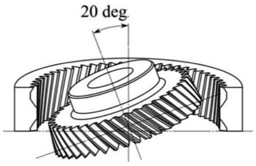
$$\alpha_T = \left(\alpha_T - \alpha_{T\min}\right) / \left(\alpha_{T\max} - \alpha_{T\min}\right) . \quad (8)$$

The subscripts "max" and "min" indicate the maximum and minimum values of evaluated ranges for each parameter, respectively. Table 3 shows the values of parameters used in Eqs. (4)-(8).

Table 3. Maximum and minimum values of each parameter.

	Min	Max
v (m/ min)	0	200
d_e (mm)	0	0.5
γ_T (deg.)	-90	90
α_T (deg.)	0	90

Table 4. Data of a cutter with a large helix angle.

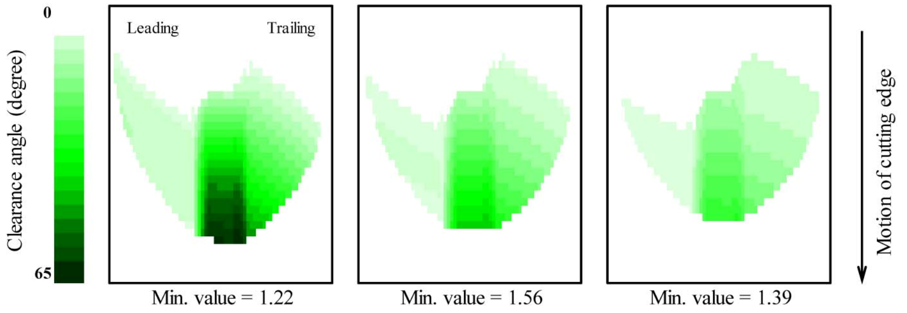
	Cutter 04	
	Left flank	Right flank
Normal module	2.0	
Number of teeth	40	
Normal pressure angle (deg.)	20.0	
Helix angle (deg.)	35(LH)	
Helix angle (deg.)	32(LH)	38(LH)
Tip diameter (mm)	101.0	
Reference diameter (mm)	97.662	
Transverse pressure angle (deg.)	24.509	25.745
Base diameter (mm)	88.862	87.968
Side relief angle (deg.)	3.0	
Front relief angle (deg.)	7.3	
Rake angle (deg.)	10.0	
Sharpening angle (deg.)	-35.0	
Schematic diagram of cutter mating gear		

The exponents in Eq. (4) should be determined by considering the degree of effects of each parameter on cutting force. However, this technique is difficult because sufficient cutting tests have not been performed. In this study, the superiority and inferiority of shaft angles can be sufficiently evaluated. Given that the cutting force increases with v and d_e but decreases with the increase of α_T and γ_T, $n_v = n_d = 1$ and $n_{Rk} = n_{Cl} = -1$ are set. Fig. 9 presents the calculation results. The shaft angle of 10° results in the maximum index among the shaft angles. The difference between the calculation result in the shaft angles of 20° and 30° is small.

Small shaft angle should be used to avoid collisions between cutters and gears or between cutter holders and gears considering that cutting forces are similar. Consequently, the shaft angle of approximately 20° provides moderate cutting conditions, considering tool life without interferences.

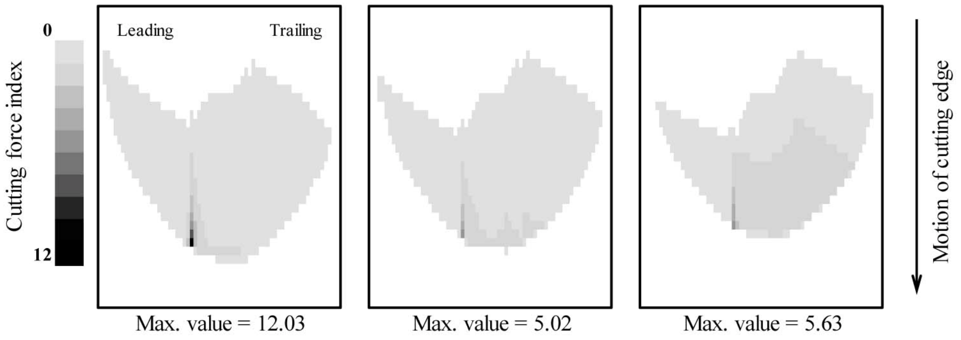
4. Specific settings

As shown in Sec. 3, the shaft angle is generally determined to incline the cutter axis to the same side of the gear helix. In this study, the effects of shaft angles on cutting tool parameters are examined in a special case, in which the cutter axis inclines opposite compared to general cases. The gear data shown in Table 1 applies also in this case. In addition, tooth profile deviations of skived gears are calculated using the cutters after re-sharpening of tool faces.



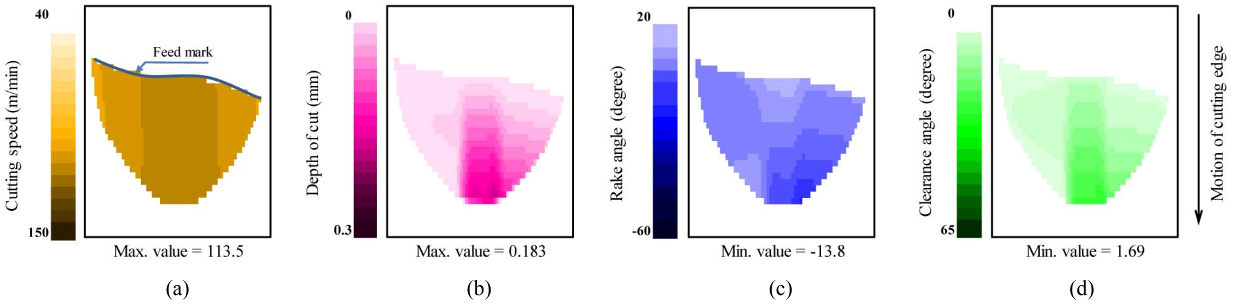
(a) (b) (c)

Fig. 8. Comparison of clearance angle: Shaft angle of (a) 10°; (b) 20°; (c) 30°.



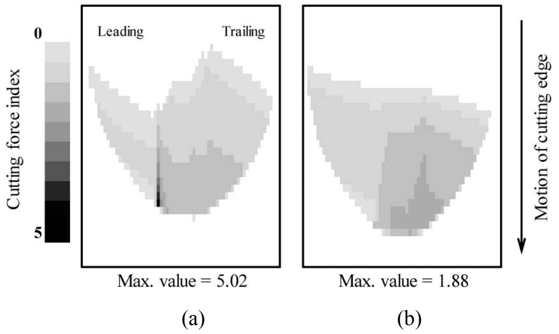
(a) (b) (c)

Fig. 9. Calculated cutting force index: Shaft angle of (a) 10°; (b) 20°; (c) 30°.



(a) (b) (c) (d)

Fig. 10. Calculation results of cutting tool parameters using the cutter with large helix angle: (a) Cutting speed; (b) cut depth; (c) rake angle; (d) clearance angle.



(a) (b)

Fig. 11. Calculated cutting force indexes: (a) Generally used setting; (b) specific setting.

4.1 Cutter with large helix angle

Cutter data are listed in Table 4. We set the helix angle at 35° (LH). This condition produces a shaft angle of 20°, in which its absolute value is the same with cutter no. 02. However, the inclination direction of cutter axis is opposite to general cases, as shown in this table.

4.2 Cutting tool parameters

Fig. 10 shows the calculation results of cutting tool parameters using a shaft angle with inclination direction opposite to general cases. The shaft angle provides a slightly higher cutting speeds, smaller depths of cut, smaller negative rake angles, and clearance angles compared with the values shown in Figs. 5(b), 6(b), 7(b) and 8(b), which are calculated with a shaft angle of 20°.

Fig. 11 shows the comparison of cutting force indexes between the specific setting and generally used setting (Different scales used compared with Fig. 9). The specific setting for a cutter with large helix angle could improve tool life. Considering the same absolute value of shaft angle, the specific setting and generally used setting have the same limitations on interferences between cutters and gears.

4.3 Skived gear profile after re-sharpening

A computer program has been developed to calculate the cutting edge with an arbitrary position of re-sharpening. In the program, the cutter is assumed to be ground with a common method using a trapezoidal wheel. This program enables the simulation of gear profile skived with the calculated cutting edge. In the previous study, the authors clarified that a cutter with a large helix angle resulted in large profile deviations of skived gear under the generally used setting [7].

In the present study, we calculated the effect of re-sharpening on a skived gear profile using a specific setting. We compared the calculated gear profiles using the cutting edges obtained with a re-sharpening amount of 0 mm and 5 mm. Only the center distances were adjusted to obtain proper tooth thickness. However, the shaft and offset angles were not adjusted. Such adjustments are currently applied in skiving.

Fig. 12 shows the calculation results. The profile deviations after re-sharpening resulted in more than 20 μm. This result caused the requirement of other or new grinding methods for taper-shaped skiving cutters to establish the specific setting with skiving cutters with large helix angles in practical application.

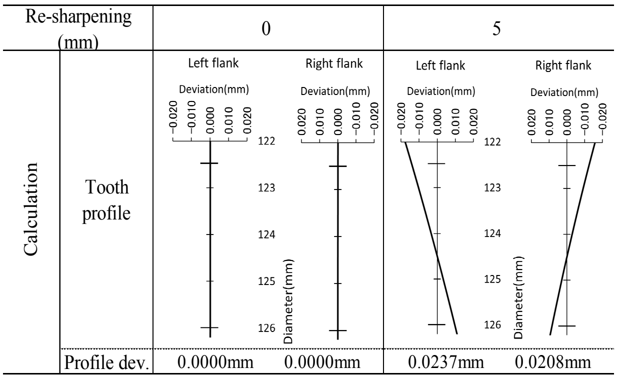

Re-sharpening (mm)		0		5	
Calculation	Tooth profile	Left flank	Right flank	Left flank	Right flank
	Profile dev.	0.0000mm	0.0000mm	0.0237mm	0.0208mm

Fig. 12. Calculations of gear profiles skived with a skiving cutter after re-sharpening of 0 mm and 5 mm.

5. Experiments

We conducted cutting tests to compare the results under generally used setting with cutter no. 02 (Table 2) and those under specific setting with cutter no. 04 (Table 4). These tests

Table 5. Cutting conditions of cutting force measurements.

Cutting conditions	Cutter 02	Cutter 04
Cutter speed (rpm)	1210	←
Rotating direction (Cutter)	CW	CCW
Sliding velocity (m/min)	121	137
Num. of pass	1	←
Feed rate (mm/w.rev)	0.05	←
Shaft angle (deg.)	20	-20
Cutting time (sec.)	43	←

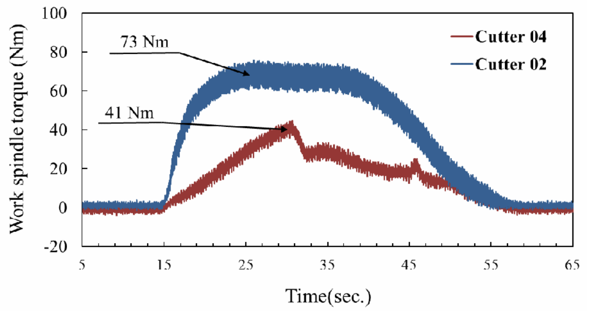


Fig. 13. Work spindle torque of cutting force tests.

were performed using a dedicated skiving machine Kashifuji KPS20. Cutting force measurements and cutter wear tests were also performed.

5.1 Cutting force measurement

5.1.1 Cutting conditions

Table 5 shows the cutting conditions of cutting force measurements. Each cutter axis inclines to different sides toward the vertical axis. In practical skiving, multi-pass cutting is applied considering gear accuracy. However, we skived gears with single-pass cutting to emphasize the difference clearly.

5.1.2 Results

Fig. 13 shows the measured motor torques applied on the work spindle during the cutting force measurement. The specific setting for skiving cutter with large helix angle resulted in lower motor torque than the generally used setting. The specific setting should provide longer tool life than the generally used setting. Cutter no. 04 produced a characteristic variation in spindle torques around the peak of torques. This condition might be attributed to the difference between the feed mark shapes shown in Figs. 5(a) and 10(a), which would cause an imbalance of cutting force on the right and left flanks. This condition should be evaluated in detail to clarify the cause of variation.


(a) (b)

Fig. 14. Example of chips generated by (a) cutter no. 02 (Small helix angle); (b) cutter no. 04 (Large helix angle).

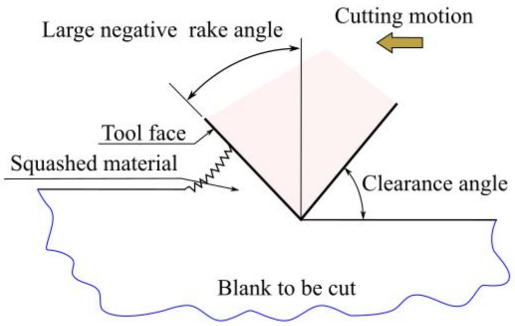


Fig. 15. Schematic of formation mechanism by the squashed chip.

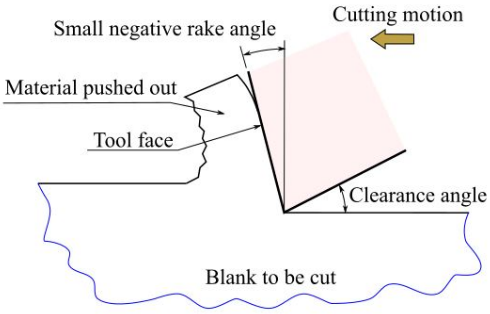


Fig. 16. Schematic of formation mechanism by the unsquashed (Pushed out) chip.

We observed forms of chips generated during the skiving processes. Fig. 14 shows the examples of chips formed in the processes by cutters nos. 02 and 04. The chip formed by cutter no. 04 has more unsquashed form than cutter no. 02. Such unsquashed chip form might be attributed to small negative rake angles (Figs. 15 and 16). The unburned chip color by cutter no. 04 shows that it generated lower cutting heat than cutter no. 02.

5.2 Cutter wear test

5.2.1 Cutting conditions

Table 6 shows the cutting conditions of cutter wear tests. We conducted three-pass cutting in these processes. In practical use of gear skiving for internal gears, such as automotive transmission gears, multi-pass cutting is currently adopted, considering tool lives and machining times.

5.2.2 Results

Fig. 17 shows the results of cutter wear tests. The specific

Table 6. Cutting conditions of cutter wear test.

Cutting conditions	Cutter 02	Cutter 04
Cutter speed (rpm)	1210	←
Rotating direction (Cutter)	CW	CCW
Sliding velocity (m/min)	121	137
Num. of pass	3	←
Feed rate (mm/w.rev)	0.2/0.2/0.05	←
Shaft angle (deg.)	20	-20
Cutting time (sec.)	62	←

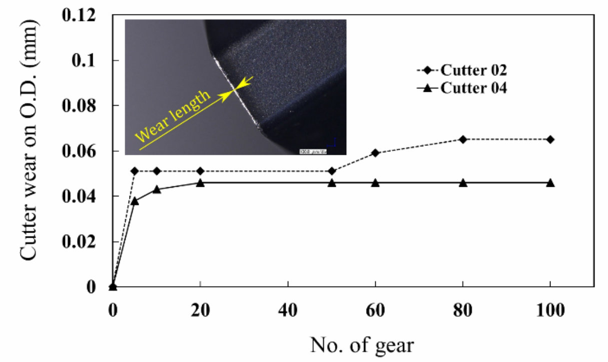


Fig. 17. Cutter wear after skiving 100 gears.

setting for skiving cutter no. 04 with large helix angle resulted in considerably less cutter wear than the generally used setting after skiving 100 gears. For investigating cutter wear, we measured the length of worn portions from the cutting edge on the O.D.

6. Conclusions

In the present study, the effects of shaft angle on cutting tool parameters in internal gear skiving were discussed to examine the generally used value of shaft angle by skiving simulations and experiments. The following results were obtained.

(1) A shaft angle of 20° results in moderate cutting conditions in which the cutting speeds, rake angles, and depths of cut are in good balance for extending tool life.

(2) The cutting forces become low when the cutter axis inclines opposite to the direction of the gear tooth helix to be skived. Therefore, such cutters can obtain lower cutter wear than those from generally used setting although they have the same limitation on interferences between cutters (or cutter holders) and gears.

(3) A cutter with large helix angle yields large profile deviations of skived gears after re-sharpening.

The profile deviations of skived gears prevent the utilization of cutters with large helix angles for internal helical gear skiving. However, the proposal has a significant potential for improving tool life, which is one of the large concerns in gear manufacturing. We will continue to examine the method of manufacturing and designing cutters with large helix angles to minimize the profile deviations of gears after re-sharpening of tool faces.

Nomenclature

θ_{off} : Offset angle
Σ : Shaft angle
$\boldsymbol{v}$: Instantaneous cutter speed
$\boldsymbol{t}$: Tangent vector to a cutting edge at a cutting point
$\boldsymbol{n}_f$: Normal vector to the tool face
$\boldsymbol{n}_t$: Normal vector to the tool flank
γ_T : Instantaneous rake angle
α_T : Instantaneous clearance angle
v : Scalar of instantaneous cutter speed
d_e : Instantaneous depth of cut

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