

# Development of design and manufacturing technology for end mills in machining hardened steel

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## Abstract

Tool geometry such as rake angle and clearance angle was clearly defined to solve the difference in communication between the design and measurement stages. Using the simulation program, the wheel was properly determined and the end mill manufactured accurately. The performance test with the well-defined end mill provided sufficient information to determine optimal geometry. In this paper, end mills for machining hardened steel were designed and manufactured. The performance test conducted yielded the optimal rake angle and clearance angle. Likewise, a specific software for automatic end mill production was developed for the simulation and generation of NC code as CAD/CAM system.

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*Keywords:* Helical flutes; Design parameters; Simulation of end mill configuration; Rake angle; Clearance angle

## 1. Introduction

The development of the CNC machining center for high speed machining (HSM) can change manufacturing systems. Using proper end mills in HSM no longer requires a finishing process such as grinding and polishing. Likewise, HSM can drastically improve machining productivity and accuracy. Therefore, HSM is considered a principal machining technology in manufacturing today. Similarly, the machining process can be improved using proper end mills in machining hardened steel like die and mold. Thus, developing a proper end mill for HSM and machining hardened steel is now strongly recommended. Nevertheless, developing proper end mills require the successful development of geometry and grade, this in turn requires both design and manufacturing technology.

It is very difficult to define end mill geometry because all the angles are generated along the helical flute. Rake angle changes along with the rake face. Rake angle and clearance angle are important factors influencing cutting performance. In end mill manufacturing, rake face and helical flute are machined at the same time. Likewise, several design factors must be satisfied simultaneously. Thus, obtaining accuracy and precision of end mill geometry is difficult due to the excessive to small change of wheel geometry and wheel

position. Nevertheless, a previously developed simulation program can be effectively used to facilitate the design and manufacture of the end mill, with proper selection of wheel geometry and wheel positions as output [3].

A program for the CNC tool grinder was developed to simulate the grinding result and generate NC code as CAD/CAM system. The end mill with varying rake and clearance angles for machining hardened steel was produced using the developed program. Likewise, cutting forces and machined surface errors were measured and compared to evaluate the cutting performance of the end mills. The experimental approach determined the optimal rake and clearance angle.

## 2. Definition of end mill geometry and measurement method

### 2.1. Definition of end mill geometry

Fig. 1 shows the design factors for end mills, e.g. diameter ( $D$ ), inscribed circle diameter ( $D_w$ ), rake angle ( $\gamma$ ), clearance angle ( $\eta$ ), and helix angle ( $\beta$ ). Rake and clearance angles are the most important among the design factors. Rake angle in particular affects stiffness of the cutting edge and rigidity of the tool. An end mill with a positive rake angle improves machinability, thereby producing lower cutting force and cutting temperature. In general, the positive rake angle is applied to the conventional end mill. In case of a negative

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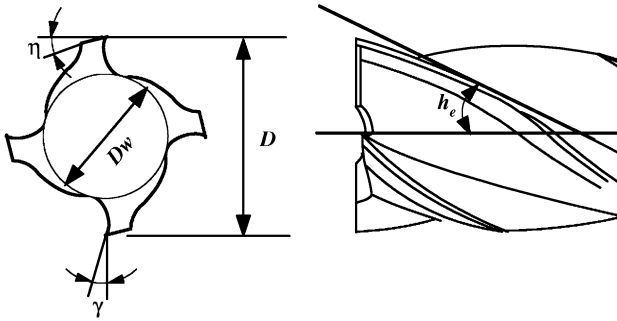


Fig. 1. Geometry of end mill.

rake angle, the stiffness of the cutting edge is increased and chipping suppressed. However, machinability declines due to the large plastic deformation in cutting. Increased helix angle induces increased effective rake angle, thereby improving machinability and accuracy. While a large clearance angle improves surface roughness, but it is easy to be chipped. On the other side, a small clearance angle is likely to produce noise and higher surface roughness.

Thus, the rake and clearance angle must be carefully determined when designing end mills, since these angles are very difficult to define due to the curved shape of the helical flute. The definition and measurement method for rake and clearance angles are determined prior to designing end mill geometry. In this research, rake and clearance angles were defined as the tangential angle at the edge to each face.

2.2. Measurement method

An optical enlargement device is usually used to measure end mill geometry. This method observes the cross-section of the end mill. Therefore, the end mill must be precisely cut in order to obtain accurate data. Likewise, measurement accuracy depends on the skill of the operator.

Measurement using optical device is nondestructive and very effective compared to the previous method. In this paper, Helicheck manufactured by Walter was used. This equipment uses laser as light source. Fig. 2 shows the scanned rake surface along the end of the edge. To determine the rake angle, several points having the same interval were selected. The line was then obtained using the least square method. Determining the measuring depth is critical for linear interpolation, since a different rake angle can be

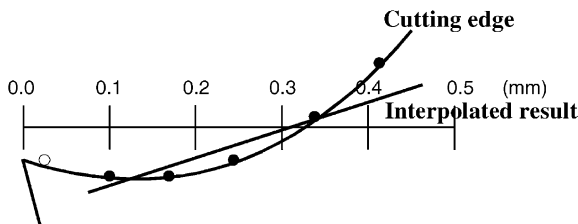


Fig. 2. Measurement method for rake angle.

obtained from the same rake face geometry according to the measuring depth. If the feed per tooth as cutting condition is very small in HSM, the measuring depth must be small. In this paper, the rake angle was defined as the tangential angle at the edge.

3. Simulation of helical groove grinding

The helical flute grinding is the most important step in the entire end mill manufacturing process, since it forms important parameters such as rake angle, inscribed circle diameter, and flute configuration. Since helical flute grinding was performed only once using the given wheel geometry, it was difficult to satisfy all the required design parameters. Trial and error method has long been used to determine cutting conditions. However, it is an expensive and time-consuming process. Thus, the simulation program for manufacturing in CNC tool grinder is essential.

3.1. Basic algorithm

The simulation algorithm for the helical groove machining in this study was based on the assumption that a wheel with finite thickness consists of a finite number of thin disks. The profile of the groove can be calculated uniquely and exactly if an exact wheel profile is used as an input [1,2]. By accumulating the points met by each thin disk with each sleeve of workpiece, the helical groove was predicted using the given wheel profile [2]. In previous research, the groove configuration was predicted as a ‘direct method’ using the same assumption [3].

Fig. 3(a) shows the typical wheel for end mill manufacturing. The wheel profile consists of two straight lines defined by angle and thickness. Fig. 3(b) shows the simulation results by thin wheel disks that are superposed at a cross-section. The helical groove configuration was obtained by selecting only the outer points. On the other hand, Fig. 4 shows the position of each wheel segment relative to the end mill. In machining, wheel position relative to end mill ( $x_0, y_0$ ) and wheel setting angle ( $\alpha$ ) are critical in determining the end mill configuration.

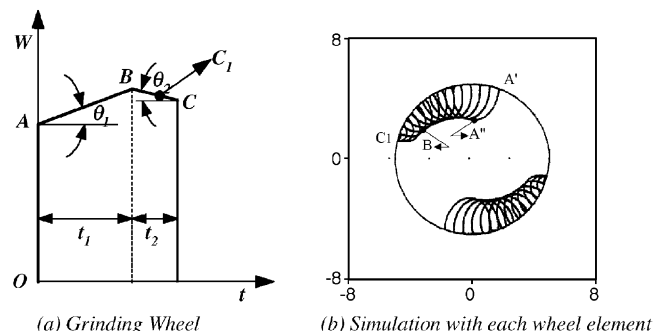


Fig. 3. Configuration of grinding wheel and simulation results.

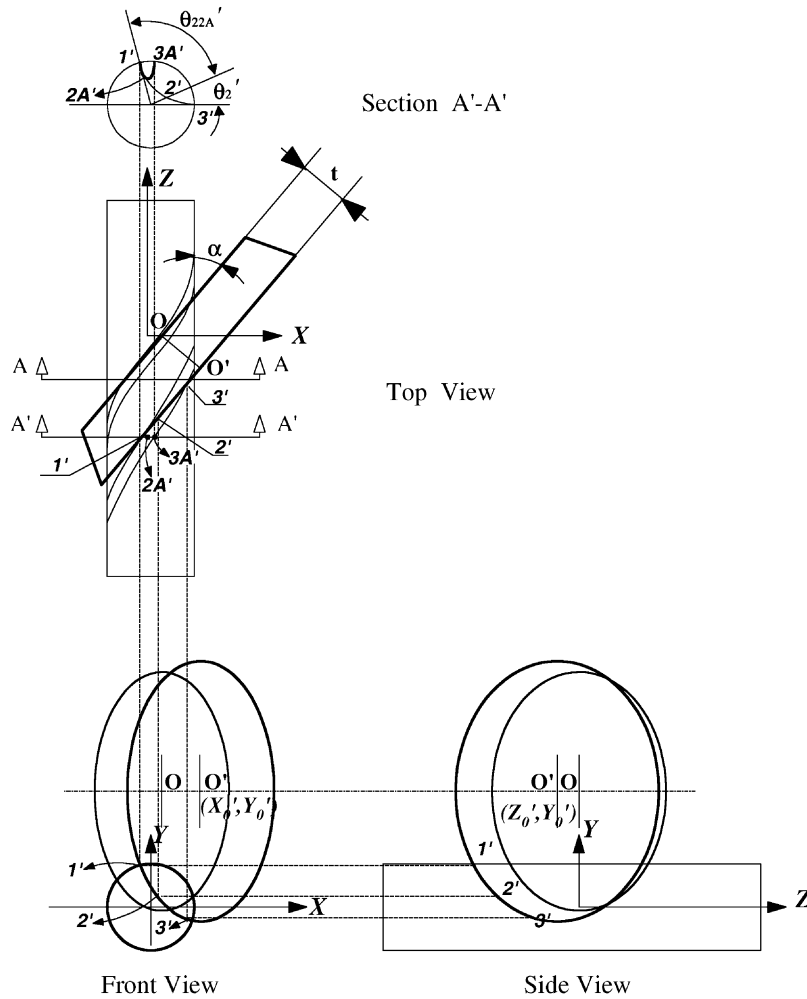


Fig. 4. Schematic illustration of helical groove operation with finite wheel thickness.

#### 4. End mill design and manufacturing technology

Satisfying end mill design parameters, determining proper wheel geometry, wheel location  $(x_0, y_0)$ , and wheel setting angle  $(\alpha)$  are required. However, it is impossible to find a unique condition to satisfy the design requirement due to the many manufacturing parameters. Thus, simulation is the most effective method in determining proper manufacturing conditions. The software was developed for the prediction of helical flute grinding. It can also be used to determine the manufacturing parameters. As a first step, wheel geometry must be determined for given design parameters. Using the selected wheel, wheel position was calculated as an output of the simulation software. Likewise, the NC code for making complete end mill was generated.

In this study, the end mill for machining hardened steel was produced. The rake angle was set as  $-14^\circ$ , with inscribed circle diameter  $(D_w)$  at 8 mm when diameter  $(D)$  is 10 mm. It contain six teeth, with helix angle  $(h_c)$  of  $45^\circ$  as a result of many tests and experiences for machining hardened steel.





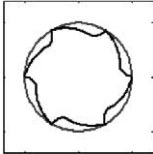
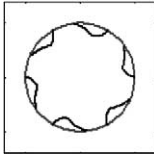
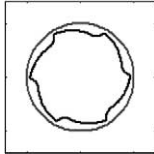
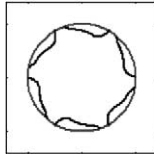
##### 4.1. Determination of wheel geometry

Based on the relationships between Fig. 3(a) and (b), the rake face  $A'A''$  in Fig. 3(b) was generated by the wheel element A in Fig. 3(a). Configuration of the helical groove  $A''B$  in Fig. 3(b) was determined by the wheel elements in section AB in Fig. 3(a). Thus, the size of the inclination angle  $\theta_1$  and thickness  $t_1$  determined the cross-sectional configuration of the end mill in section  $A''B$  in Fig. 3(b). The part of flute  $BC_1$  in Fig. 3(b) was produced by the wheel element BC in Fig. 3(a). BC is the recess of the end mill for generating the clearance angle in Fig. 1. When the end mill does not contain recess like the end mill for HSM, the wheel without the part BC is sometimes used.

Table 1 shows the simulation results of the end mill sectional configuration with varying wheel shapes. Proper wheel geometries must be determined prior to machining the helical flute for the end mills designed as above. Sometimes, it is impossible to machine the desired helical flute with an improper wheel.

Four kinds of wheels were suggested as shown in Table 1. Even though the cross-section requirement seemed to be

Table 1  
Influence of the various wheel geometry on cross-sectional configuration in helical flute grinding

	(a)	(b)	(c)	(d)
$t_1$	4	4	4	2.2
$t_2$	0	0	0	2
$\theta_1$	14	0	20	15
$\theta_2$				
Wheel shape				
Simulation results				
	Overcut	Under cut	Overcut	Proper

satisfied, it did not contain the margin to generate the designed clearance angle (Table 1(a)). This case wheel also affected the cutting edge during grinding (over cut). Increased inclination angle from  $-14^\circ$  to  $-20^\circ$  (Table 1(c)) showed more severe over cut. The inclination angle decreased from  $-14^\circ$  to  $0^\circ$ ; thus, a very large part was left for the clearance face (Table 1(b)). Since the final cutting edge is generated after the operation of the clearance face, light machining is usually required. The most optimized cross-section was generated using the wheel as shown in Table 1(d). Such wheel contained two steps of inclination angles. Thus, the most optimized wheel configuration was obtained from the simulation using four different wheel geometries. The end mill configuration changed according to the relative wheel position ( $x_0, y_0$ ) and wheel setting angle ( $\alpha$ ), even though the same wheel was considered. Likewise, the variation of the wheel setting angle ( $\alpha$ ) depended on the rake angle.

4.2. End mill design with a given wheel

Table 2 and Fig. 5 present simulated results with varying rake and clearance angles by a given wheel (d) in Section 4.1. Simulation yielded the rake angle and wheel position ( $x_0, y_0$ ) for end mill manufacturing. The wheel position in particular was determined in order to satisfy rake angle. Thus, the same wheel position was obtained in case of the same rake angle (Table 2). Fig. 5(a) shows the simulated results with varying rake angles ( $-10^\circ, -14^\circ$  and  $-17^\circ$ ).

The tool position was determined based on the rake angle and inscribed circle. The wheel setting angle ( $\alpha$ ) was fixed.

Clearance face was machined as shown in Fig. 6 using wheels with inclination angle. Eq. (1) shows the relationship among clearance angle ( $\eta$ ), wheel inclination angle ( $\theta_e$ ), and helix angle ( $h_e$ ):

$$\eta = \tan^{-1} \left( \frac{\tan \theta_e}{\tan h_e} \right) \tag{1}$$

Clearance angle was defined as the tangent angle at the edge of the clearance face. In this research,  $5^\circ, 10^\circ$ , and  $14^\circ$  were used as clearance angles to make end mills.

Fig. 5(b) shows the simulation results with varying clearance angles. In the operation of the clearance face, the wheel was located at the center of the end mill and perpendicular to the axis of the end mill. The effect of rake and clearance angle on the performance of the end mill was also evaluated for optimal design.

4.3. Development of software for automatic end mill grinding

The end mills are usually produced by the CNC tool grinder to increase productivity and accuracy. The end mill operation consists of the helical flute, clearance face, gashing, and end teeth processes. Thus, the specific program for the CNC Tool grinder not only involves the simulation of configuration but also the generation of NC codes for each process as well.

Table 2  
Determination of wheel position for designed rake angle and wheel inclination angle for designed clearance angle

	(A)	(B)	(C)	(D)	(E)
Rake angle ( $\gamma$ )	$-10^\circ$	$-14^\circ$	$-17^\circ$	$-14^\circ$	$-14^\circ$
Clearance angle ( $\eta$ )	$10^\circ$	$10^\circ$	$10^\circ$	$5^\circ$	$14^\circ$
Wheel position for rake angle ( $x_0, y_0$ )	(31.55, 65.41)	(34.29, 62.76)	(36.28, 60.61)	(34.29, 62.76)	(34.29, 62.76)
Wheel inclination angle ( $\theta_e$ ) for clearance angle	$10^\circ$	$10^\circ$	$10^\circ$	$5^\circ$	$14^\circ$

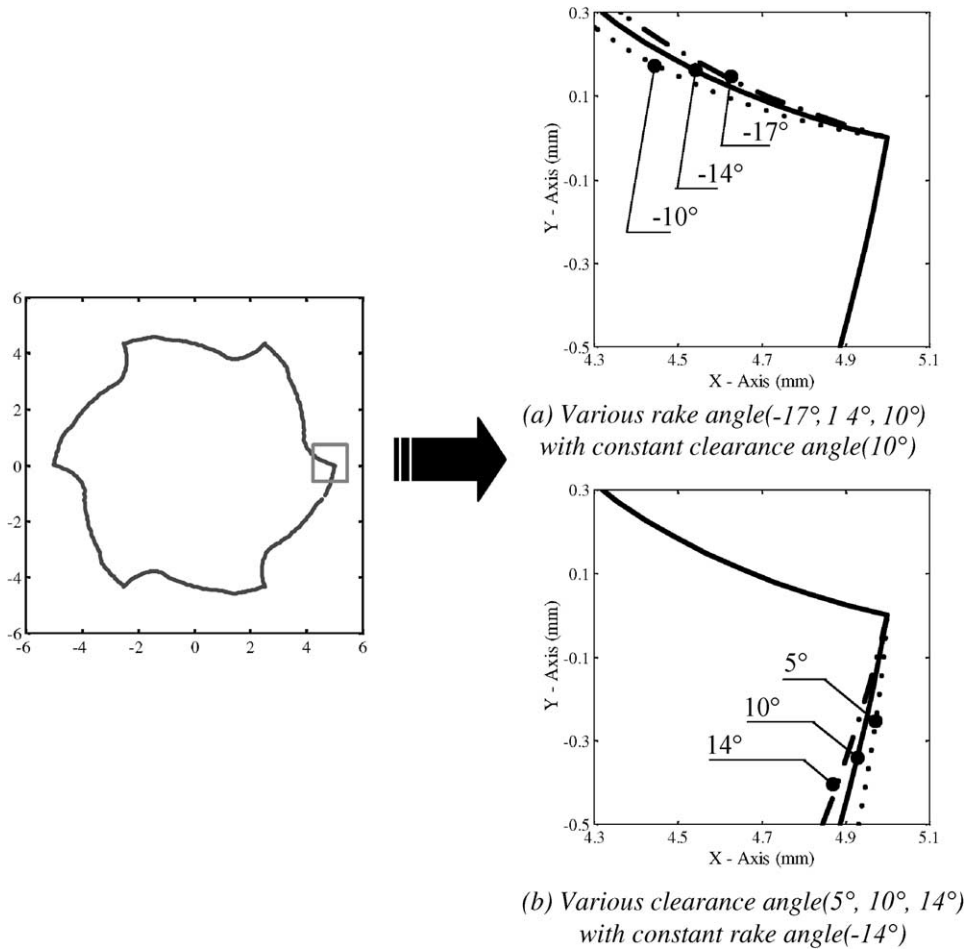


Fig. 5. Simulation results with various rake angles (a) and clearance angles (b).

Table 3 lists the end mill design factors and wheel geometries as input parameters. These design factors must be inputted as shown in Fig. 7(a) and (b); ditto for machining parameters such as distance between axes. Four kinds of wheels are usually used, with each wheel defined separately as shown in Fig. 7(b) and Table 3. The helical flute grinding formed a helical flute and rake face as shown in Fig. 5, which are the most important and the most difficult to operate factors in determining end mill cutting performance. Thus, this paper introduced only the algorithm for helical flute grinding. The other operations are composed of the straight movement of the wheel and the end mill, which make

predicting grinded results easier. Fig. 7(c) shows the simulated configuration of the end mill. The end mill design factor and wheel geometry were verified according to these simulation results.

Each machining process performs rotation and translation of the axis of wheel and tool. The initial and final position of each process must be calculated during simulations to make generation of NC code easier. Table 3 lists the calculated positions for wheel ( $x_0, y_0, z_0, B$ ) and end mill ( $x_e, y_e, z_e, C$ ).  $B$  and  $C$  were the rotational positions of wheel and end mill, respectively.

Information on initial and final position of wheel and end mill is sometimes a great help to the operator. This information was obtained from this program as output and stored in a

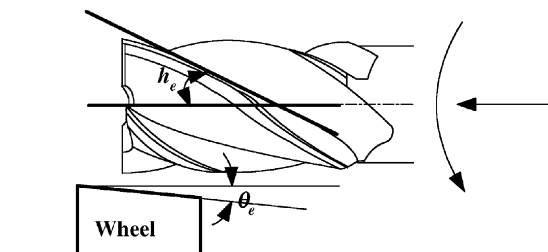
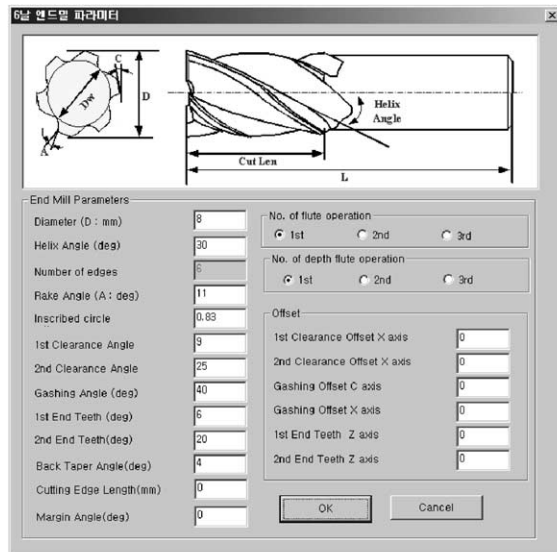


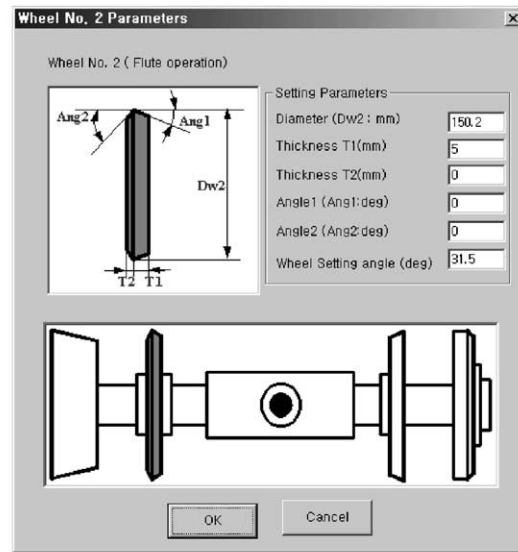
Fig. 6. Schematic illustration of operation for clearance face.

Table 3  
Design and manufacturing factors for end mill grinding

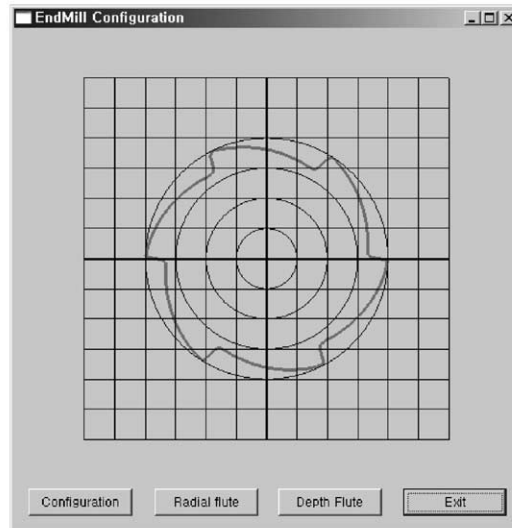
End mill	Helix angle ( $h_e$ ), diameter ( $D$ ), rake angle ( $\gamma$ ), inscribed circle diameter ( $D_w$ ), clearance angle ( $\eta$ )
Wheel nos. 1–4	Diameter, $t_1, t_2, \theta_1, \theta_2$ for each wheel
Machining data	Wheel rotation angle ( $\alpha$ ), wheel position ( $x_0, y_0, z_0, B$ ), end mill position ( $x_e, y_e, z_e, C$ )



(a) Input window for end mill design parameters



(b) Input window for grinding wheel geometry parameters



(c) Simulation results with given design parameters

Fig. 7. Some windows of the program for automatic manufacturing end mill.

separate file. These position data are used to generate NC code. In addition, the solver that predicts machining results and calculates machining parameters was developed using Fortran for calculation and Visual C++ for graphical user interface.

## 5. Evaluation of the influence of design and manufacturing parameters on cutting performance

### 5.1. Manufacturing of end mill samples

Using the developed program, design parameters and proper wheel geometries were determined to produce the end mill for machining hardened steel. Table 4 lists the rake

and clearance angles designed for samples. End mills (A), (B), and (C) were designed to maintain varying rake angles of  $-10^\circ$ ,  $-14^\circ$  and  $-17^\circ$  with a constant clearance angle of  $10^\circ$ , respectively. On the other hand, end mills (D), (B), and (E) were designed to maintain varying clearance angles of  $5^\circ$ ,  $10^\circ$  and  $14^\circ$  with a constant rake angle of  $-14^\circ$ , respectively. The other design factors were held constant. Fig. 8 shows the sample (E) in Table 4. The end mill was cut by wire EDM, with the cross-section also shown. To evaluate the machining accuracy and the simulation results, one of the cutting edges was measured by tool microscope and compared with the simulation results in Fig. 8. The comparison showed very good correspondence between them.

The samples were measured using Helicheck to verify the rake angle and clearance angle. The rake angle in particular

Table 4  
Comparison of designed and measured geometry of end mill samples

	Design		Measurement			
	Rake angle ( $\gamma$ )	Clearance angle ( $\eta$ )	Rake angle ( $\gamma$ )		Clearance angle ( $\eta$ )	Clearance width
			0.2	0.45		
(A)	-10	10	-11.29	-12.55	11.59	0.967
(B)	-14	10	-15.18	-19.3	11.54	0.907
(C)	-17	10	-18.63	-20.97	11.42	0.952
(D)	-14	5	-12.4	-23.3	6.35	0.473
(E)	-14	14	-15.97	-16.35	15.42	1

Table 5  
Cutting conditions for performance tests

Material property	Workpiece	SKD11
	H <sub>R</sub> C	45
Cutting condition	Axial depth of cut	10 mm
	Radial depth of cut	0.2 mm
	Feed rate	0.03 mm per tooth
	Cutting speed	2400 rpm

was defined as the tangent angle at the cutting edge. Therefore, the rake angle measured at 0.2 mm from the cutting edge showed better correspondence with the designed value compared to that at 0.45 mm (Table 4). The measurement error at the measuring machine was also considered.

5.2. End mill performance test

Cutting tests were conducted to verify the cutting performance of five end mills on these samples (Table 4). Table 5 shows the cutting conditions for side cutting. The cutting performance tests were already carried out with respect to

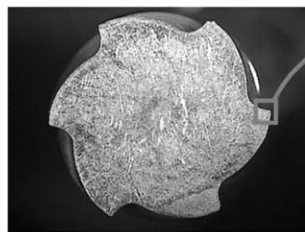
the change in the helix angle. The effect of the change in rake angle was not considered due to the difficulty in measurement and definition. Nevertheless, this research clearly showed the definition and measurement of the rake angle. Thus, every result caused by the change in geometry can be analyzed correctly.

The influence of the clearance angle was investigated to determine the optimal geometry of the end mill [4–6]. While the change in clearance angles were declared in all research, determining the exact measurement is difficult. For this study, accurate measurements were carried out by the Heli-check which ensured the verifiability of the result.

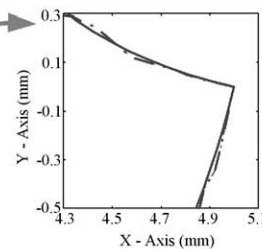
Fig. 9 shows the cutting force and surface error in side end milling. It shows influences of decreasing rake angle from  $-10^\circ$  to  $-17^\circ$  at a constant clearance angle of  $10^\circ$ . A negative rake angle caused the increase of the cutting force in the Y-direction which is normal to the feed direction. Likewise, increasing rake angle increased surface error, which was measured using laser distance sensor (Fig. 9). Fig. 10 shows similar results, with varying clearance angles ( $5^\circ$ ,  $10^\circ$ ,  $14^\circ$ ) at a constant rake angle of  $-14^\circ$ . Increasing the clearance angle decreased the cutting force in the Y-direction; thus, clearly



(a) End mill sample using developed program with condition Table 2(E)



(b) Cross section of end mill



(c) Comparison of measured and simulated results

Fig. 8. Example of end mill samples and comparison of measured and simulated results.

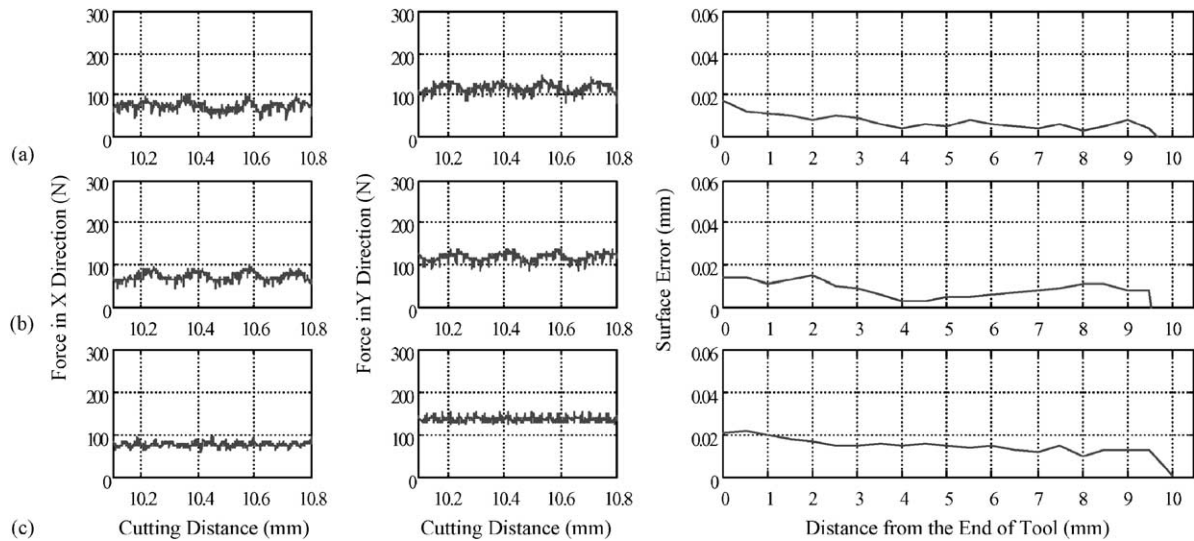


Fig. 9. The influence of rake angle on cutting force and surface error in end milling with constant clearance angle ( $10^\circ$ ): (a) rake angle =  $-10^\circ$ , (b)  $-14^\circ$  and (c)  $-17^\circ$ .

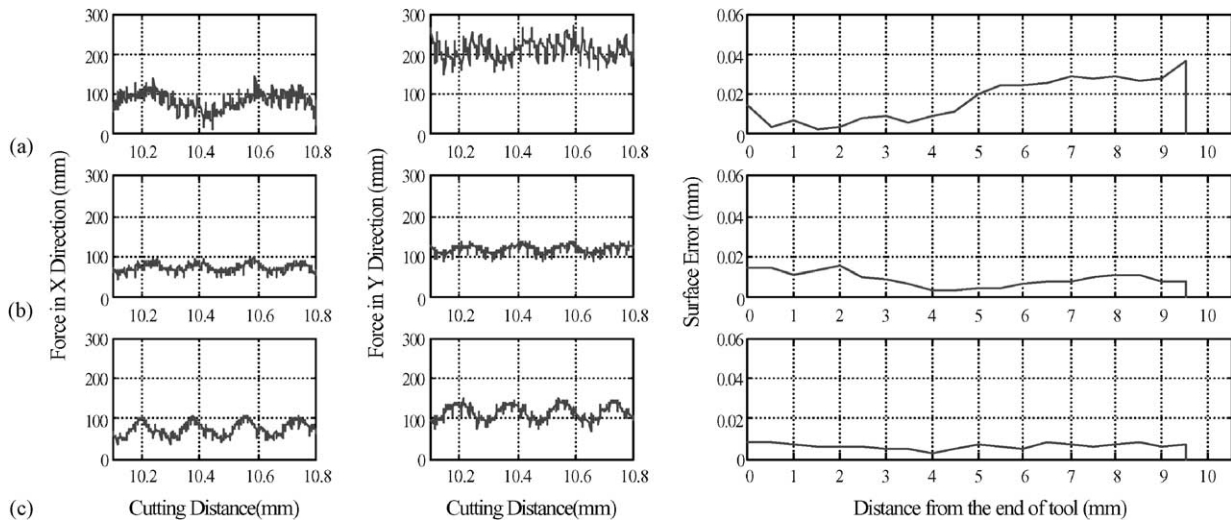


Fig. 10. The influence of clearance angle on cutting force and surface error in end milling with constant rake angle ( $-14^\circ$ ): (a) clearance angle =  $5^\circ$ , (b)  $10^\circ$  and (c)  $14^\circ$ .

indicating the influence of the clearance angle. The importance of the clearance angle became more evident by changing the surface error. In the end mill with a small clearance angle like Fig. 10(a), friction behavior on the flank face intensified; thus, the cutting system became unstable as shown in the measured cutting force.

Finally, the end mill (E) in Table 2 was considered as the optimum end mill geometry. The optimal rake angle was  $-14^\circ$ , with clearance angle of  $14^\circ$  and diameter of 10 mm for the machining hardened steel. Similar to the design and manufacture of high performance end mill, clear definition and accurate measurement of geometry must precede the design. This method can determine the optimal geometry which is critical in increasing productivity and quality of the end mill for various workpieces.

## 6. Conclusions

Based on the results of this study, the following conclusions can be drawn:

1. The simulation program for helical flute grinding was developed and applied to the design and manufacture of the end mill by predicting the cross-sectional configuration.
2. The program for automatic tool grinding using the CNC tool grinder was developed based on the simulation program. The NC code generated as CAD/CAM system served as program output.
3. Optimal rake angle and clearance angle were determined, considering the change in surface error in the performance test according to the change in geometry.

4. The whole process for the design and manufacture of end mill with high cutting performance was suggested based on the simulation program of the helical flute grinding.

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