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Optimization of Processing Conditions According to Run-out During End-mill Round Machining

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엔드밀 원형 가공 시 런아웃에 따른 가공조건 최적화

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ABSTRACT

With the increased utilization of CAM programs, end-mill processing is most commonly used for machining and metal processing. In particular, hole or shaft machining has high assembly precision, which inevitably leads to high utilization of end mills. However, the analysis of quality characteristics according to the process conditions of end mills is not performed systematically at the site, causing poor quality and productivity. The most influential factor of quality is the runout of the end mill. In this paper, the number of turns of the end mill, number of tool blades, cutting direction, and artificial runout volume were determined to identify the correlation between the epicenter, cylindricality, and surface roughness. Two types of end mills, three levels of runout, three levels of rotational speed, and two cutting directions were considered and 36 rounds of hole processing were conducted. For the analysis of shape characteristics according to the set process variables, the experimental planning method was applied to the measured specimen and the processing characteristics were analyzed according to the runout of the end mill through correlation analysis.

Keywords : End-mill(엔드밀), Run-out(런아웃), Process Conditions(공정조건), Finishing Allowance(정삭여유량), Optimization(최적화)

1. Introduction

The end milling process of high-speed machining centers has become common with the development of machinery and metal processing. Because parts used in the aerospace, robotics, and semiconductor equipment industries require particularly high precision[1], and because high-quality products are manufactured within a short delivery time at the sites where small batch production is common, the end milling process is frequently utilized. As the utilization of CAM programs increases, the end milling process of high-speed machining centers is applied to shape processing beyond general processing methods (e.g., side cutting process, groove milling process, and surface process). For example, the end milling process has become more

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frequent in circular arc processing, shaft processing, contour processing, and 3D processing.

Previous studies have investigated the cutting force of end milling considering the shape behavior of the cutting force generated by the run-out of the tool holder[2]. Kline[3] and Kline and Devor[4] developed a cutting model that considered cutting instrument, tool radius, chip thickness, and entry/exit angles of tools to predict the characteristics of cutting force at the time of tool run-out. Another study was conducted to provide the optimum finish allowance required for improving processing accuracy and productivity by examining the relationship between the finish allowance and the processing accuracy obtained therefrom[5]. In addition, through the end milling process in high-speed machining centers, the change in vibration in the run-out of the tool was measured for each rotational speed of the spindle with a displacement sensor to determine the effect on the surface roughness of the product[6].

Many studies have been conducted according to process variables, including tool rotation speed (RPM), number of end mill teeth, cutting direction, depth of cut, and cutting feed. However, there is a lack of research on the effects of the run-out amount on quality characteristics, which can be easily measured by the operator at the sites, as well as the optimum finish allowance.

This study investigates the machining characteristics of the run-out amount according to the cutting direction in machining the hole shape, which is the shape-processing shaft of the end mill in a high-speed machining center, and further provide the optimum finish allowance for in-advance preventing defects of gouging occurring due to arbitrary depth of cut by each worker. For these purposes, this study has intentionally generated the shape of the whole and shaft run-out at the AL6061 base material, which is most commonly used for weight reduction in the aerospace, robotics, high-tech parts, and semiconductor equipment parts industries, under the conditions of the same process variables, the number of rotations, the number of tool teeth, and cutting direction at the same depth of finishing cut and processing, in order to investigate the correlation between roundness, cylindricalness, and surface roughness in quality characteristics.

2. Experimental Subject and Method

2.1 Experimental Devices and Objects

The equipment used in this experiment was VERTICAL CENTER NEXUS 510C-II, manufactured by MAZAK; specifications are shown in Table 1.

The specimen used in this experiment was the AL6061 material, which is widely used in the aerospace, robotic equipment, and semiconductor equipment industries.

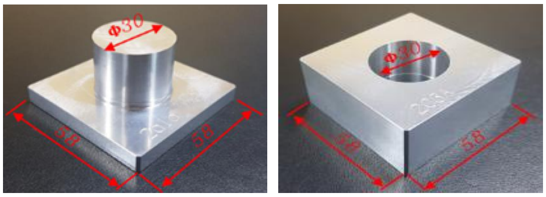
Fig. 1 shows a specimen for the machining experiment; 36 pieces each were prepared with a size of 58 × 58 × 30 [mm] with a shape of a ϕ 30 shaft and a ϕ 30 hole within a control tolerance of 0.01 mm.

For the aluminum end mill, TaeguTec's 2F and 3F tools were used. Fig. 2 shows a typical shape, and Table 2 describes the detailed specifications of the end mill.

After machining, the Deokin Coordinate

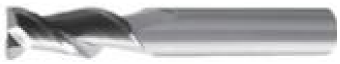
Table 1 Specification of the machining center

Ability.volume	Table length	1300 mm
	Table width	550 mm
principal axis	Taper type	BT 40
	RPM	12,000
	Motor output	11 kW / 15.0 HP
Automatic tool exchange device	Number of tools	30 ea
Movement	X-axis travel	1050 mm
	Y-axis travel	530 mm
	Z-axis travel	510 mm



(a) Shaft specimen (b) Hole specimen

Fig. 1 Specimen of the machining test



(a) 2F end mill

(b) 3F end mill

Fig. 2 Configuration of a typical end mill

Table 2 Specification of the end mill

Material	Cemented carbide	
End mill outer diameter	ϕ 10	
Number of end mill blades	2F	3F
Number of flutes [EA]	3	3
Tool length [mm]	68	68
Flute length [mm]	25	25
Helix angle [˚]	45	45

Measuring Machine was utilized to measure the roundness and cylindricalness of the shape of the shaft, as well as the hole, as quality characteristics. The surface roughness was measured by using Mitutoyo's SJ-210 Roughness Measuring Instrument.

2.2 Process Variables and Conditions

The end mills for the machining experiment have the shapes of ϕ10 × 2F and ϕ10 × 3F; three of each which were prepared for the three different run-out amounts. The end mills were mounted onto the spindle of the machining center within a range of 0.1 mm by using milling chuck and collet.

Table 3 Cutting speed per edge of end mill

RPM	Cutting feed [mm/min]	
	2F(0.04/tooth)	3F(0.03/tooth)
3,000	240	270
6,000	480	540
12,000	960	1080

Measurement was performed with an indicator, and the run-out amounts were set to 0.007 mm, 0.040 mm, and 0.070 mm, respectively. The rotational speed (RPM) of the spindle was set in the low-speed (3,000), medium-speed (6,000), and high-speed (12,000) modes. The cutting feed was calculated according to Equation (1) by referring to the feed per tooth, and the results are presented in Table 3.

$$F = f_t \times Z \times N \qquad (1)$$

where, F : feed speed [mm/min]

f_t : feed amount per tooth [mm]

Z : number of teeth [ea]

N : number of rotations [rpm]

The specimen was fixed by using the Samchully Power Vice PCV-160 model to prevent any problem in the quality characteristics due to the clamping force, and the test was performed by setting it to stage 0.

The cutting depth was set to twice the tool diameter and proceeded with 20 mm. In the semi-finish cutting, the process was performed once at the depth of cut of 0.25 mm per side, and in the finish cutting, the process was performed twice at the depth of cut of 0.0 2mm per side. Table 4 shows the cutting conditions for creating a CAM program.

As experimental conditions, the process variables including number of rotations, number of tool teeth, and cutting direction were varied to perform 36 tests or hole-shaped specimen processing, as well as 36 tests for shaft-shaped specimen processing.

Table 4 Cutting conditions

End mill	ϕ10 x 2F	ϕ10 x 3F
Runout value[mm]	0.007 / 0.04 / 0.07	
Spindle speed[RPM]	3,000 / 6,000 / 12,000	
Roughing	0.25mm [1 rotation]	
Finishing	0.02mm [2 rotation]	
Cutting depth	20mm [2 x d]	
Cutting direction	CW / CCW	
Cutting shape	Shaft / Hole	
Cutting methods	Up and down millings	

Because it is difficult to identify the conditions of process variables with the naked eye, specimens were individually engraved.

3. Analysis of Physical Quantities According to Process Variables

Tables 5 and 6 show hole machining results according to the number of end mill teeth, rotational speed, cutting direction, and run-out amount (process variables), and Tables 7 and 8 show shaft machining results. Symbol ○ represents roundness, ⌭ represents cylindricality, ⏦ represents surface roughness, CCW represents up cutting, and CW represents down cutting.

4. Finishing Allowance Optimization

4.1 Optimization of Machining Conditions

To derive the optimal conditions for roundness, cylindricalness, and surface roughness during the end milling process in the high-speed machining center in considering the effects of the process variables (number of rotations according to the run-out amount, the number of tool teeth, and the cutting direction) on the quality characteristics of the hole shape machining, this study has derived the optimization conditions as shown in Fig. 3 by using the minimum value obtained from the factorial analysis of the method of experiments (DOE) as the optimization tool under the process variable conditions including 3,000 rotations , two tool

Table 5 Quality characteristic result data (2F)

Number of tool blades					2F					
Run out	Division				A		B		C	
	Set point				0~0.03mm		0.04~0.06mm		0.07~0.09mm	
	Experimental value				0.0070mm		0.040mm		0.070mm	
RPM	1	Making no./Cutting direction			2A1 (CCW)	2A1A (CW)	2B1 (CCW)	2B1A (CW)	2C1 (CCW)	2C1A (CW)
		3,000	○	[mm]	0.0102	0.0136	0.0166	0.0163	0.0116	0.0127
			⌭	[mm]	0.0170	0.0214	0.0287	0.0392	0.0334	0.0645
			⏦	[㎛]	0.1800	0.2340	0.1320	0.4960	0.2170	0.5500
	2	Making no./Cutting direction			2A2 (CCW)	2A2A (CW)	2B2 (CCW)	2B2A (CW)	2C2 (CCW)	2C2A (CW)
		6,000	○	[mm]	0.0126	0.0161	0.0100	0.0175	0.0131	0.0140
			⌭	[mm]	0.0170	0.0254	0.0233	0.0391	0.0357	0.0619
			⏦	[㎛]	0.1870	0.2130	0.1470	0.3780	0.2080	0.4850
	3	Making no./Cutting direction			2A3 (CCW)	2A3A (CW)	2B3 (CCW)	2B3A (CW)	2C3 (CCW)	2C3A (CW)
		12,000	○	[mm]	0.0133	0.0146	0.012	0.0146	0.0137	0.0177
			⌭	[mm]	0.0298	0.0248	0.0272	0.0360	0.0396	0.0698
			⏦	[㎛]	0.1730	0.6420	0.1580	0.4650	0.2180	0.4610

Table 6 Quality characteristic result data (3F)

Number of tool blades					**3F**					
Run out	Division				A		B		C	
	Set point				0~0.03mm		0.04~0.06mm		0.07~0.09mm	
	Experimental value				0.007mm		0.040mm		0.070mm	
RPM	1	Making no./Cutting direction			3A1 (CCW)	3A1A (CW)	3B1 (CCW)	3B1A (CW)	3C1 (CCW)	3C1A (CW)
		3,000	○	[mm]	0.0142	0.0129	0.0115	0.0157	0.0124	0.0139
			⌭	[mm]	0.0245	0.0191	0.0180	0.0320	0.0462	0.0369
			〰	[μm]	0.1020	0.2110	0.0970	0.0436	0.1080	0.4300
	2	Making no./Cutting direction			3A2 (CCW)	3A2A (CW)	3B2 (CCW)	3B2A (CW)	3C2 (CCW)	3C2A (CW)
		6,000	○	[mm]	0.0149	0.0132	0.0126	0.0132	0.0137	0.0151
			⌭	[mm]	0.0194	0.0166	0.0198	0.0325	0.0456	0.0378
			〰	[μm]	0.0760	0.1730	0.1490	0.3200	0.1180	0.5250
	3	Making no./Cutting direction			3A3 (CCW)	3A3A (CW)	3B3 (CCW)	3B3A (CW)	3C3 (CCW)	3C3A (CW)
		12,000	○	[mm]	0.0130	0.0135	0.0127	0.0137	0.0156	0.0134
			⌭	[mm]	0.0182	0.0151	0.0219	0.0302	0.0503	0.0398
			〰	[μm]	0.0670	0.1600	0.1610	0.3450	0.1740	0.4400

Table 7 Quality characteristic result data (2F)

Number of tool blades					**2F**					
Run out	Division				A		B		C	
	Set point				0~0.03mm		0.04~0.06mm		0.07~0.09mm	
	Experimental value				0.007mm		0.040mm		0.070mm	
RPM	1	Making no./Cutting direction			2a1 (CW)	2a1a (CCW)	2b1 (CW)	2b1a (CCW)	2c1 (CW)	2c1a (CCW)
		3,000	○	[mm]	0.0105	0.0149	0.0145	0.0126	0.0154	0.0112
			⌭	[mm]	0.0162	0.0203	0.0237	0.0210	0.0404	0.0369
			〰	[μm]	0.2410	0.2570	0.4590	0.3500	0.6230	0.5730
	2	Making no./Cutting direction			2a2 (CW)	2a2a (CCW)	2b2 (CW)	2b2a (CCW)	2c2 (CW)	2c2a (CCW)
		6,000	○	[mm]	0.0132	0.0148	0.0185	0.0109	0.0179	0.0157
			⌭	[mm]	0.0190	0.0210	0.0274	0.0220	0.0484	0.0429
			〰	[μm]	0.2840	0.5060	0.4240	0.7030	0.4830	0.5250
	3	Making no./Cutting direction			2a3 (CW)	2a3a (CCW)	2b3 (CW)	2b3a (CCW)	2c3 (CW)	2c3a (CCW)
		12,000	○	[mm]	0.0166	0.0162	0.0157	0.0148	0.0157	0.012
			⌭	[mm]	0.0259	0.0231	0.0277	0.0271	0.0448	0.0399
			〰	[μm]	0.2630	0.2250	0.5170	0.2020	0.6810	0.4550

Table 8 Quality characteristic result data (3F)

Number of tool blades					3F					
Run out		Division			A		B		C	
		Set point			0~0.03mm		0.04~0.06mm		0.07~0.09mm	
		Experimental value			0.007mm		0.040mm		0.070mm	
RPM	1	Making no./Cutting direction			3a1 (CW)	3a1a (CCW)	3b1 (CW)	3b1a (CCW)	3c1 (CW)	3c1a (CCW)
		3,000	○	[mm]	0.0145	0.0137	0.0114	0.0132	0.0167	0.0123
			⌭	[mm]	0.0155	0.0138	0.0399	0.0362	0.0482	0.0408
			〰	[㎛]	0.1950	0.1460	0.4240	0.3450	0.7210	0.3810
	2	Making no./Cutting direction			3a2 (CW)	3a2a (CCW)	3b2 (CW)	3b2a (CCW)	3c2 (CW)	3c2a (CCW)
		6,000	○	[mm]	0.0134	0.0131	0.014	0.0116	0.0176	0.0126
			⌭	[mm]	0.0164	0.0161	0.0386	0.0337	0.0505	0.0441
			〰	[㎛]	0.2020	0.1890	0.3300	0.4190	0.4680	0.4870
	3	Making no./Cutting direction			3a3 (CW)	3a3a (CCW)	3b3 (CW)	3b3a (CCW)	3c3 (CW)	3c3a (CCW)
		12,000	○	[mm]	0.0154	0.0114	0.0157	0.0113	0.0162	0.0121
			⌭	[mm]	0.0190	0.0167	0.0395	0.0330	0.0474	0.0441
			〰	[㎛]	0.1890	0.1700	0.3520	0.2940	0.4860	0.3450

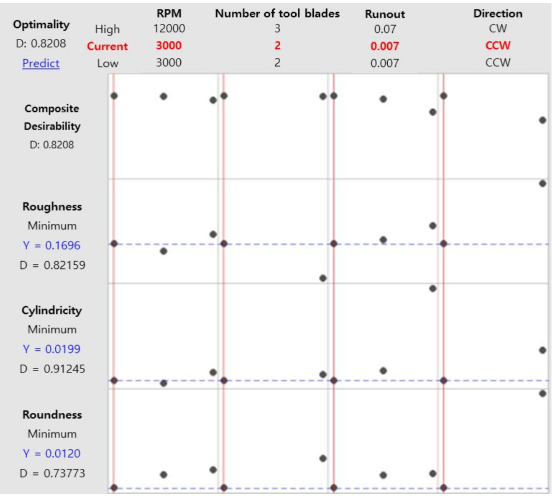


Fig. 3 Optimization plot of hole end milling (Minimum)

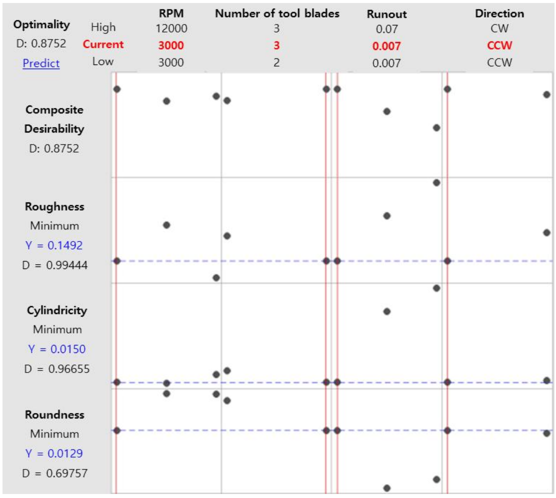


Fig. 4 Optimization plot of shaft end milling (Minimum)

blades, run-out of 0.007 mm, and cutting direction of CCW.

This study further derived the optimization conditions regarding the shaft processing under the same process variable conditions, other than the number of tool blades of three, as shown in Fig. 4.

The fact that the number of rotations affects the result, suggests that the vibration generated by the increase in the number of rotations have some effects. In addition, the result suggests that the

CCW is advantageous in discharging chips compared to the CW.

4.2 Derivation of Finish Allowance

This study has derived optimal conditions to find the finish allowance for overcutting through an arbitrary depth of cut in machining the hole shape of the end mill. Using the results obtained from the factorial analysis of the DOE as the optimization tool, the finish allowance was derived as 0.06 mm or more under the process variable conditions including 12,000 rotations, two tool teeth, run-out of 0.07 mm, and cutting direction of CW. Fig. 5 shows the optimization result under the worst conditions. In machining the shaft shape of the end mill, the optimum conditions for the finish allowance were derived for preventing defects of gouging occurring due to arbitrary depth. Using the results obtained from the factorial analysis of the DOE as the optimization tool, the finish allowance was derived as 0.0454 mm or more under the process variable conditions, including 12,000 rotations, two tool teeth, run-out of 0.07 mm, and cutting direction of CW. Fig. 6 shows the optimization result that derives under the worst conditions.

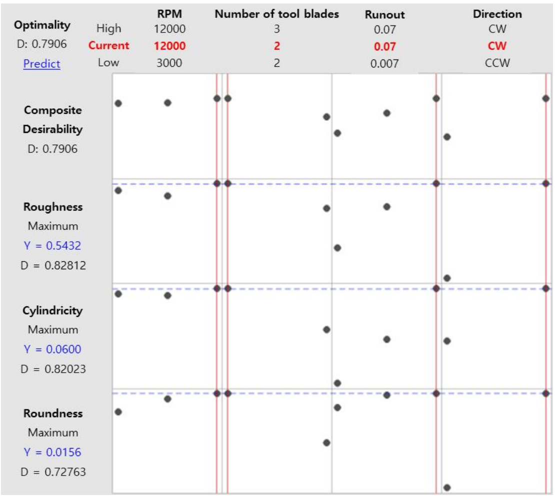


Fig. 5 Optimization plot of hole end milling (Maximum)

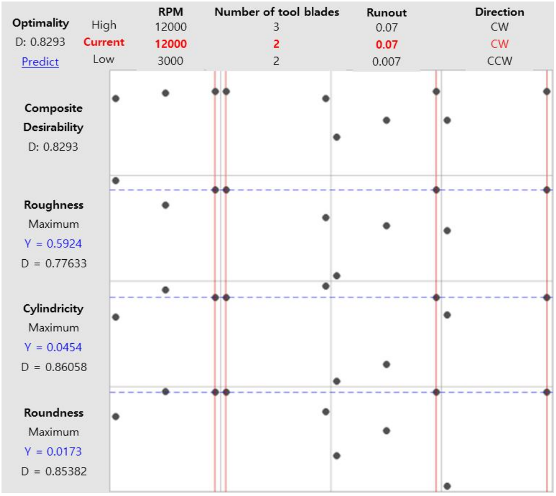


Fig. 6 Optimization plot of shaft end milling (Maximum)

4.3 Validation

This study investigated the effects of the run-out amount on the number of rotations, the number of toll teeth, and the cutting direction in machining the hole shape, which is the shape processing shaft of the end mill in a high-speed machining center, and further determined the optimum finish allowance for in advance preventing defects of gouging occurring due to arbitrary depth of cut by each worker. According to the validation of finish allowance, the roundness in quality characteristics was found to be insignificant in the experiment. Because the surface roughness is not related to the finish allowance, it is necessary to verify the validity of the finish allowance according to the cylindricity. Thus, using the optimal conditions derived in the previous section, the validity of the finish allowance was verified by repeating the hole and shaft shape machining 12 times each under the worst conditions.

Fig. 7 shows a graph of 12 repeated experiments to verify the validity of the finish allowance in the

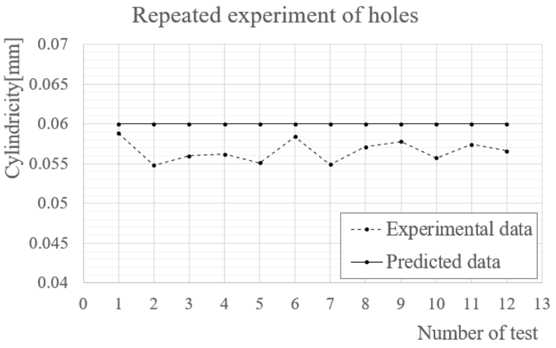


Fig. 7 Repeated experiment of holes

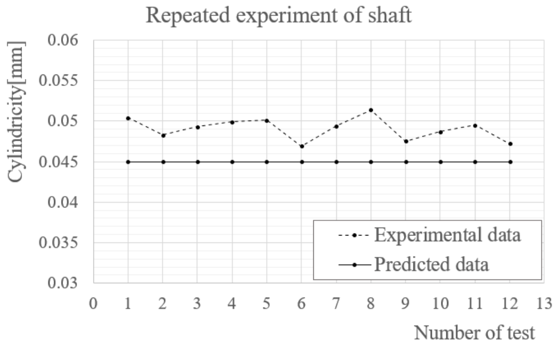


Fig. 8 Repeated experiment of shaft

hole shape processing experiment. The average deviation range was found to be 0.003 mm.

Fig. 8 shows a graph of 12 repeated experiments to verify the validity of the finish allowance in the shaft shape processing experiment. The average deviation range was found to be 0.004 mm.

5. Conclusion

This study, during the end milling process in a high-speed machining center, has analyzed the process characteristics through the DOE in the experiment of the hole and shaft shape processing regarding the AL6061 base material according to the process variables including number of rotations, number of tool teeth, and cutting direction according to run-out, and further found and verified the optimum finish allowance for in-advance prevention of defects of gouging occurring due to arbitrary depth of cut by each worker.

The run-out amount during the end milling process of hole and shaft shapes had an effect on the cylindricity and surface roughness in quality characteristic, and the effect on roundness was small. The optimal and worst conditions were found through the DOE, and the mean deviation range was confirmed by repeating experiments under worst conditions.

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