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A Study on Effect of Tool Wear Rate upon Cutting Tool Shape in a Titanium Rough Cut Machining

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티타늄 황삭가공에 있어서 공구형상이 공구마모율에 미치는 영향에 관한 연구

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ABSTRACT

The aviation industry has grown beyond the simple processing and assembling of aircraft parts and now designs and exports finished aircraft. In this study, the vertical CNC milling rotational speed and feed rate were parameters to investigate the life of tools according to their shape: (flat, round, and ball end mill) in the rough cutting of titanium. These tools are widely used in aircraft manufacturing and assembly. The purpose of this study is to measure the cutting temperature generated during the cutting process and calculate the rate of tool wear. This will be accomplished by measuring the tool weight before and after cutting the specimen and to compare it with the results of previous studies. Our study showed that the maximum cutting temperature increased as cutting time, tool rotational speed, and feed rate increased. The highest cutting temperatures were recorded for the ball, round, and flat end mill, respectively. Tool wear for the ball, round, and flat end mill increased as the speed and feed rate increased. The flat end mill exhibited the highest rate of wear from a minimum of 0.62% to a maximum of 2.88%.

Key Words : Flat End Mill(평면 엔드밀), Round End Mill(라운드 엔드밀), Ball End Mill(볼 엔드밀), Vertical CNC Milling(수직 CNC밀링), Rotational Speed(회전속도), Feed Rate(이송속도), Maximum Cutting Temperature(최대 절삭온도), Wear Rates of Tool(공구 마모율)

1. Introduction

The aviation industry in Korea has grown into one that designs aircraft in-house beyond the simple processing of aircraft parts and assembly and exporting the finished products. Moreover, the technologies for part-cutting used in aircraft and composite material development used inside aircraft fuselages have improved dramatically. The demand for parts in the aircraft industry is not as high as in others, but although the production quantity is low,

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the quality of the parts needs to satisfy higher precision, reliability, and stability than in other industries. In addition, aircraft parts are processed in multi-axial processing machines compared to those in other industries due to their many complex shapes and curvatures. Aluminum and titanium account for more than half of the total parts that are used in aircraft. Titanium has high-strength material characteristics so that the cutting resistance at the cutting edge of an end-mill during cutting is high, resulting in cutting chips adhering to the cutting edge. This causes difficulties in normal cutting which requires high heat and causes high temperatures in the tools, thereby rapidly wearing them out and shortening their lifetime. In addition, its strength is high which makes it is difficult to cut, so productivity is low due to the surface roughness of the machined parts. The cutting of aircraft parts is divided into two processes: rough machining for shaping while leaving the cut allowance and finishing to improve the shape dimensions, surface roughness, and geometric tolerance of the product.The aim of the study is to determine the maximum time that plane, round, and ball end-mills can be used when performing rough machining of titanium by measuring the cutting temperature generated during the cutting process with parameters for spindle revolutions per minute (RPM) and the feed rate of vertical computer numerical control (CNC) milling. The weight of the tool was measured before and after specimen cutting to calculate the tool wear rate followed by an investigation of tool lifetime through a comparison with the results of a previous study[1].

2. Experimental device and method

2.1 Experimental device

The CNC milling apparatus used in this study was designed for vertical 3-axis high-speed cutting (D Company, Korea): its maximum spindle RPM is 12,000 and the maximum feed rate at the X and Y axes is 12,000 mm/min. Table 1 reports the main specifications of the CNC milling apparatus.

The end-mill used in the titanium cutting experiment (T Company, Korea) uses a 30° edge angle with four edges and R 3 mm round and ball end-mills whose specifications are the same with the ultra-lightweight alloy plane end-mill where the surface is coated with TiAN. Fig. 1 presents and Tables 2, 3, and 4 summarize the specifications and shapes of the end-mills.

Titanium used in the cutting experiment is a metal whose strength-to-mass ratio is the largest. Its strength is as strong as that of steel whereas its density is half of steel. It is a high-performance metal that is used in the aviation industry but is classified as a material that is difficult to cut.

Table 1 Specifications of vertical CNC milling

Type		VM5400
Maximum rotational speed (rpm)		12000
Maximum feed rate (mm/min)	X axis	12000
	Y axis	12000
	Z axis	12000
Maximum table stroke (mm)	X axis	1020
	Y axis	540
	Z axis	530
Table size (mm)		1200 × 540
Controller		Fanuc 32i
Spindle shank type		BT40

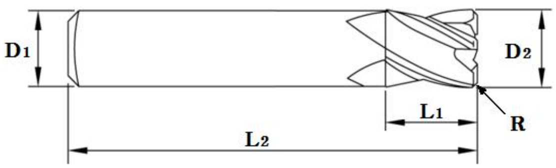

Fig. 1 Shape of end mill

Table 2 Dimensions of flat end mill

D_1(mm)	D_2(mm)	L_1(mm)	L_2(mm)	R(mm)
20	20	45	110	0

Table 3 Dimensions of round end mill

D_1(mm)	D_2(mm)	L_1(mm)	L_2(mm)	R(mm)
20	20	45	110	3

Table 4 Dimensions of ball end mill

D_1(mm)	D_2(mm)	L_1(mm)	L_2(mm)	R(mm)
20	20	45	110	10

Table 5 Mechanical properties of titanium

Ultimate strength	1,012 MPa
Yield strength	935 MPa
Break elongation	20 %
Hardness (HRC)	36

The specimen was machined into a cube shape (400 × 400 × 400 mm) and a CNC milling NC program was generated using the CATIA program for cutting according to the tool shape for 60 min in the cutting experiment. Table 5 gives the mechanical properties of the specimen. In previous studies[2-4], the surface roughness was better when using a water-insoluble cutting oil rather than a water-soluble cutting oil but combustion of the former occurred due to the high-temperature titanium chips generated during the cutting process. Thus, a water-soluble cutting oil for nonferrous metals (Z Company, overseas) was used in this study for lubrication and cooling of the specimens and tool during cutting. The recommended mixing ratio by the cutting oil manufacturer was 10:1 between water and cutting oil (Table 6 summarizes its properties).

2.2 Experimental method

In the cutting experiment, the specimen was rigidly fixed using a hydraulic chuck to prevent vibration during cutting at a cutting depth of 4 mm and a tool path interval of 14 mm (70% of the full load), and then the end-mills were attached to the two axes of the CNC milling apparatus to conduct the cutting experiment for 60 min. Table 7 gives the cutting machining conditions. For cutting the tool shapes used in the experiment, the wet cutting was conducted using plane, round, and ball end-mills under the following conditions: spindle RPM from 1,000 to 1,600 with increments of 200 RPM and feed rates from 60 to 120 mm/min with increments of 20 mm/min.

The heat measurement generated in the specimen and tool during cutting was conducted by mounting a portable infrared thermometer to the CNC milling spindle using a magnet. The focus of the thermometer was aimed at 300 mm away from the edge of the end-mill. Table 8 reports the main specifications of the portable infrared thermometer.

An electronic scale (P Company, overseas) was used to measure the wear amount of the cutting tool. For accurate weight measurements, the end-mill was cleaned with alcohol prior to cutting machining, and the weight was measured with the electronic scale. Cutting was conducted for 60 min according to the experimental conditions after which the cutting tool was cleaned with alcohol and the weight was measured via the same method used prior to cutting. Table 9 gives the main specifications of the electronic scale.

Table 6 Physical properties of water soluble coolant

Density (15℃)	DIN EN ISO 12185	980 kg/m^3
Viscosity (20℃)	DIN 51 562	135 mm^2/s
PH value (5 % in H_2O)	DIN 51 369	9.3
Cast iron chip test (1 : 20)	DIN 51 360/T2	Corrosion degree 0
Water hazard class, concentrate	-	2
Water hazard class, emulsion	-	1
Mineral oil content	142-22-0	34 %

Table 7 Machining conditions

End mil shape	Flat, round, ball
Rotational speed (rpm)	1000, 1200, 1400, 1600
Feed rate (mm/min)	60, 80, 100, 120
Axial depth of cut (mm)	4
Radial depth of cut (mm)	14
End mill diameter (mm)	20
Machining time (min)	60
Coolant	Water soluble

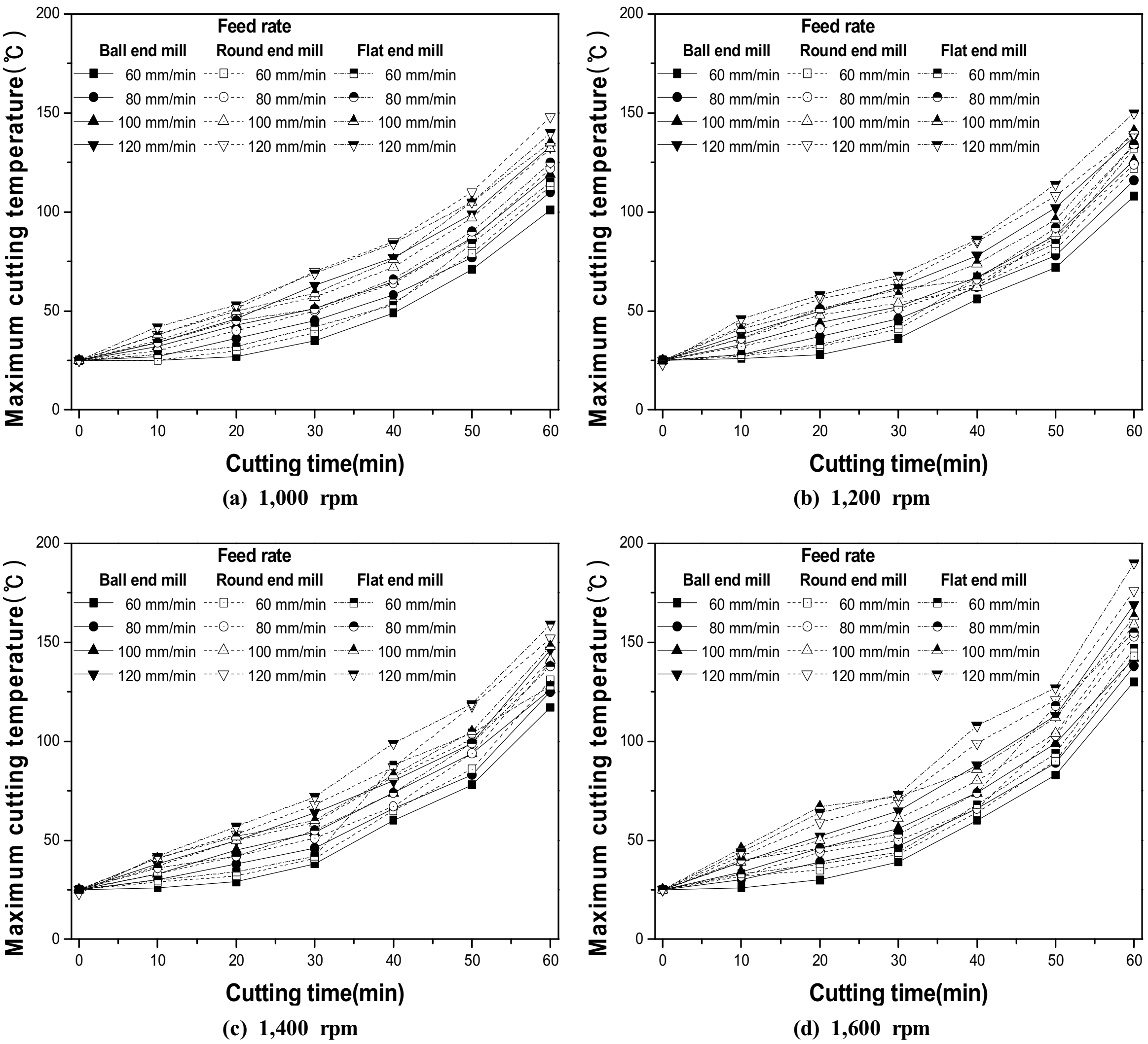

Fig. 2 Effect of machining time on the maximum cutting temperatures of ball, round and flat end mill for the respective cutting tool rotational speed as a parameter of feed rate in the axial cutting depth 4 mm and radial cutting depth 14 mm.

Table 8 Specifications of portable thermometer

Type	FLUKE568
Temperature measuring range (℃)	- 40 ~ 650
Accuracy (℃)	±1.0
Spectral response (μ m)	8 ~ 14
Response time (s)	below 0.5
Spot size (mm)	19
Interface type	USB 2.0

Table 9 Specifications of electronic scale

Type	XT 1220M
Maximum weighing range (g)	1220
Taring range subtractive (g)	1220
Linearity (mg)	+1.5 ~ -1.5
Calibration system (SCS)	built-in

3. Experimental results and discussion

3.1 The maximum cutting temperature

Fig. 2 shows the maximum cutting temperature generated at the cutting surface of the specimen and the cutting portion of the end-mill according to cutting time while changing the feed rate and RPM of the ball, round, and plane end-mills when the cutting depth and tool path interval were 4 and 14 mm, respectively. The cutting experiment was performed while maintaining the temperatures of the experimental room and cutting oil at 25 ℃ for the same experimental temperature condition. As shown, the maximum cutting temperature increased with increases in the cutting time, cutting tool RPM, and feed rate of the ball, round, and plane end-mills. This is because friction increased as the cutting tool RPM and cutting time increased, and the cutting amount per edge of the cutting tool increased as the feed rate increased. This result is consistent with those in the previous study[1].

The maximum cutting temperature was the highest in the plane end-mill followed by the round and ball end-mills. For example, the maximum cutting temperature was different by up to 123.08% between the ball and round end mills, and up to 135.38% between round and plane end-mills, and up to 135.38% between the ball and plane end-mills. This occurred because the cutting surface in the experiment was flat rather than curved and friction with the machining surface occurred for a certain period of time in the tool running after end-mill cutting, thus heat was generated by the contact with the plane, round, and ball end-mills at of 10, 7, and 0 mm, respectively.

The maximum cutting temperature of the ball, round, and plane end-mills and its increase rate were the highest after 50 min of cutting time, which was because the cutting edge was deformed, worn, and damaged as the heat generated during the cutting process accumulated in the cutting tool as a result of increased cutting time. The titanium chips had changed color due to partial oxidation during this process. The machining surface was significantly different before and after 50 min, which could be verified visually. In addition, the increase in noise generated during cutting could be felt after 50 min.

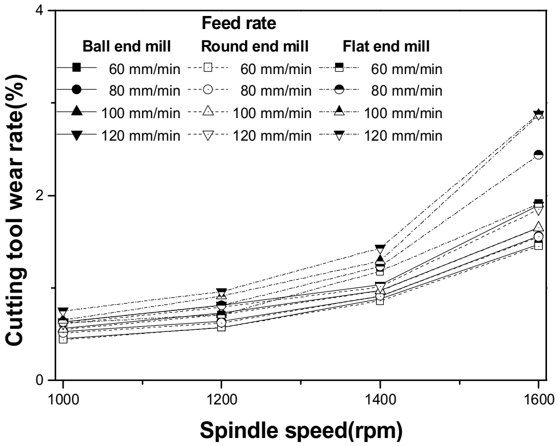

Fig. 3 Effect of cutting tool rotational speed on the wear rates of cutting tool for ball, round and flat end mill as a parameter of cutting tool feed rate in the axial cutting depth 4 mm and radial cutting depth 14 mm

3.2 The end-mill wear rate

Fig. 3 shows the wear rate according to the end-mill RPM with parameters for the feed rate of the ball, round, and plane end-mills. The end-mill weights before and after cutting for 60 min were measured, after which the wear rate was calculated as a percentage. As shown, the wear rate of the cutting tool increased with increasing RPM and feed rate of the ball, round, and plane end-mills. This was because the cutting amount per blade of the end-mill increased as the feed rate increased, thus the friction area and time increased in the end-mill and specimens increased as a result of the increase in the RPM of the end-mill. This was the same as for the maximum cutting temperature in the previous

Fig. 4 Optimal cutting tool rotational speed and feed rate of vertical CNC milling calculated by CATIA V5 tool maker program

discussion.

Fig. 4 shows the calculation results of the lifetime of the cutting tool and the optimal cutting conditions using CATIA V5 tool maker program to produce the life and optimal cutting conditions of the cutting tool. The maximum RPM and maximum feed rate were theoretically calculated as 1,440 RPM and 100 mm/min, respectively. When the calculated maximum RPM and feed rate of the cutting tool were compared with those in Fig. 3, the results exhibited that the wear rate of the tool suddenly increased at over 1,400 RPM spindle rotation speed and the highest tool wear rate was found at a feed rate of 120 mm/min for the ball, round, and plane end-mills, which indicates that the calculated results using the theoretical and actual cutting processes were similar. As shown in Fig. 3, the wear rates of the ball, round, and plane end-mills were from 0.45% to 1.89%, 0.44% to 1.85%, and 0.62% to 2.88%, respectively, which shows that the wear rate of the plane end-mill was the highest. This was because much more heat was generated due to the larger contact area when cutting with the plane end-mill, and the deformation, damage, and wear as stress occurred during cutting was concentrated at the tip of the edge.

4. Conclusions

In this study, the cutting temperature generated during the cutting process and tool weights before and after cutting a specimen were compared to measure the tool wear with parameters for RPM and feed rate of the cutting tool to determine the life of the cutting tool according to tool shape (plane, round, or ball end-mill) for the rough machining of titanium. The main comparison results are as follows:

1. The maximum cutting temperature increased with cutting time, cutting tool RPM, and feed rate of the ball, round, and plane end-mills. It was the highest in the ball end-mill followed by the round and plane end-mills.
2. The maximum cutting temperatures when using ball, round, and plane end-mills were compared, showing that they were different by up to 123.08% between the ball and round end-mills, 135.38% between the round and plane end-mills, and 135.38% between the ball and plane end-mills, which indicates that the plane end-mill had the highest maximum cutting temperature.
3. The cutting tool wear rate of the ball, round, and plane end-mills increased with increasing RPM and feed rate. The wear rate of the plane end-mill was the highest (from 0.62% up to 2.88%).
4. The results using the theoretical and actual cutting conditions were nearly the same: the maximum RPM and feed rate of the cutting tool calculated with the CATIA V5 tool maker program were 1,440 RPM and 100 mm/min, respectively, while those under actual cutting test conditions were 1,400 RPM and 120 mm/min, respectively.

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