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A study on the surface shape and roughness of aluminum alloy for heat exchanger using ball end milling

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Abstract. Aluminum alloy is a material with a high strength-weight ratio and excellent thermal conductivity. It neither readily corrodes nor quickly weakens at low temperatures, but can be easily recycled. Because of these features, aluminum heat exchangers are widely used in aluminum alloy. In addition, the aluminum alloy used in other areas is expected to gradually increase. As a result, researchers have been continuously studying the cutting patterns of aluminium alloy. However, such studies are fewer than those on the cutting patterns of ordinary steel. Moreover, the research on ball end milling with aluminium alloys has not received much attention. Therefore, in this study, an attempt was made to find the optimal cutting pattern among the seven cutting patterns for the machining of the commonly used aluminum alloy using ball end milling for a heat exchanger. The optimal pattern was found by comparing the different shapes and surface roughness values produced by the seven patterns.

1. Introduction

Aluminum is one of the most abundant metals on Earth. In most cases, it is used in the form of an alloy, which is stronger, except for foil, which is used for wrapping.

Aluminum alloy is used to make heat exchangers such as air conditioners and heaters. Its use is expected to increase in various fields. Thus, studies on the cutting theory relevant to aluminum alloy have been performed.

End milling is the most widely used method of cutting machining. Ball end milling is the most widely used method of finishing a curved surface shape.

In the machining field, demand for free-form surface machining has gradually increased. This demand has led to the abilities to design and machine complicated three-dimensional (3D) shapes, and has driven the development of the CAD/CAM software and machine tool manufacturing techniques. Due to the continuous development of the CAD/CAM software, various cutting pattern methods have been developed, and diverse tool paths can be generated. This study aims to find the optimal cutting pattern for the machining of aluminum alloy using a ball end mill by machining the alloy through the generation of different tool paths based on the seven cutting patterns shown in Figure 2 and by comparing the shapes and surface roughness values of the machined surfaces.

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2. Experimental equipment and method

2.1. Experimental Equipment

2.1.1. Machining Center. The machining center used in this experiment was TNV-40A (Tongil Heavy Industries Co., Ltd.).

2.1.2. Measuring Device . The surface roughness measuring device used in this experiment was model Surfcoder-F3500D (Kosaka Laboratory Corporation).

The shape-measuring device used in this experiment was model Hommel_C8000 (Hommelwerke).

2.2. Experimental tool and material

2.2.1. Experimental tool. The cutting tool used in this experiment was an uncoated general-purpose carbide end mill, which is used to machine free-form surfaces of metal molds.

2.2.2. Experimental material and shape. The specimen used in this experiment had a 70x70x19mm free-form surface shape. In the rough machining, a flat end mill was used, and 0.5 mm was left for finishing. In the finishing, it was machined as shown in Figure 1, using a ball end mill. The chemical composition and mechanical properties of the specimen are summarized in Tables 1 and 2.

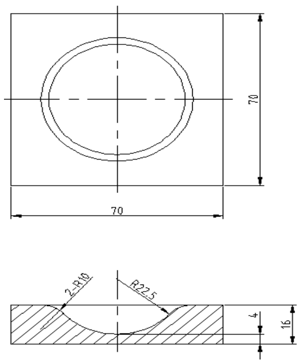


Figure 1. Dimensions of the workpiece

Table 1. Chemical composition

Workpiece material	Chemical composition							
	Cu	Si	Mg	Zn	Mn	Cr	Fe	Al
Al6061	0.15-0.4	0.4-0.8	0.8-1.2	0.25 and below	0.15 and below	0.04-0.35	0.5 and below	The rest

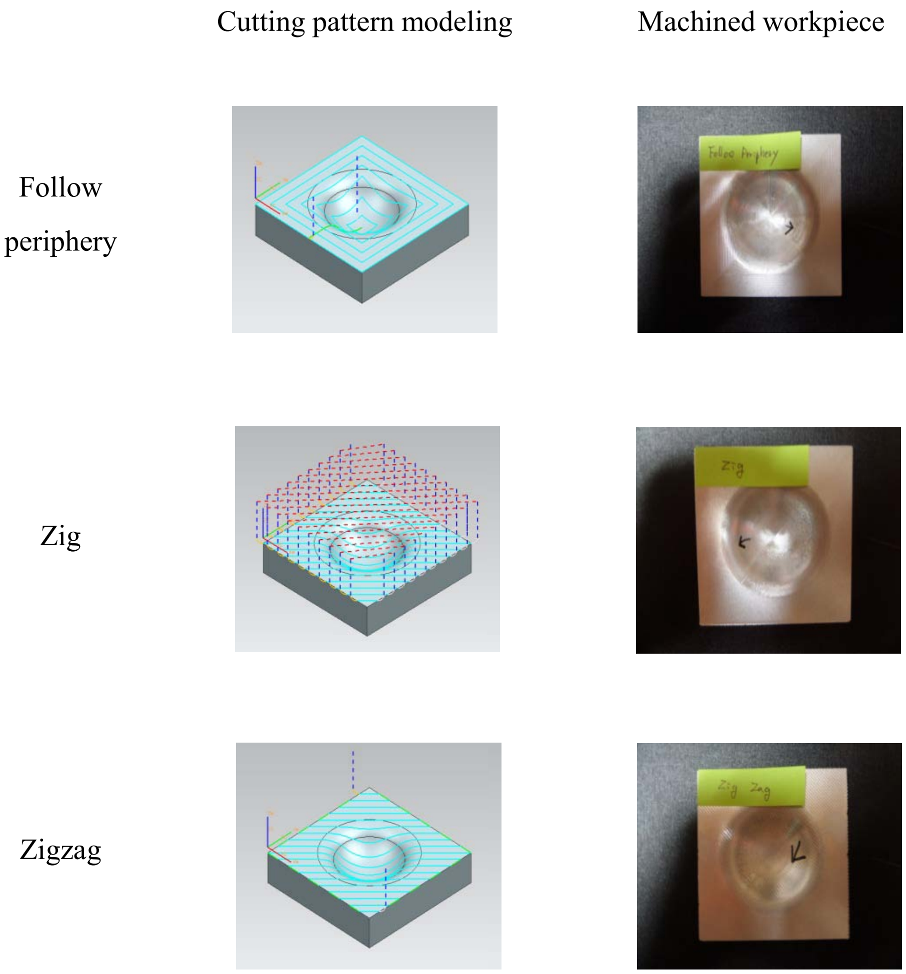
Table 2. Mechanical properties of specimen

Workpiece materia	Tensile strength (N/mm^2)	Yielding strength (N/mm^2)	Elongation (%)	Hardness (HBS 10/500)
Al6061	125	55	25	30

2.3. Experiment method

2.3.1. Specimen Modeling and Tool Path Generation. Before the specimens were machined, 3D modeling was performed using the NX program, which is the CAD/CAM software of Siemens. In the program, the machining conditions were assigned, and tool paths were generated for each cutting pattern. Based on the simulation function of the program, the shapes after the machining were verified in advance, and it was checked if there was a problem. Finally, the NC codes of the rough machining and the finishing were generated.

In the rough machining, all the specimens were identically machined in a '⊏' form along the contour of the machining shape from the outside to the inside. In the finishing, the machining was conducted by generating tool paths using the seven cutting patterns based on down-cutting, which has been verified in a number of surface roughness studies. Figure 2 shows the tool paths and the shapes after the machining.



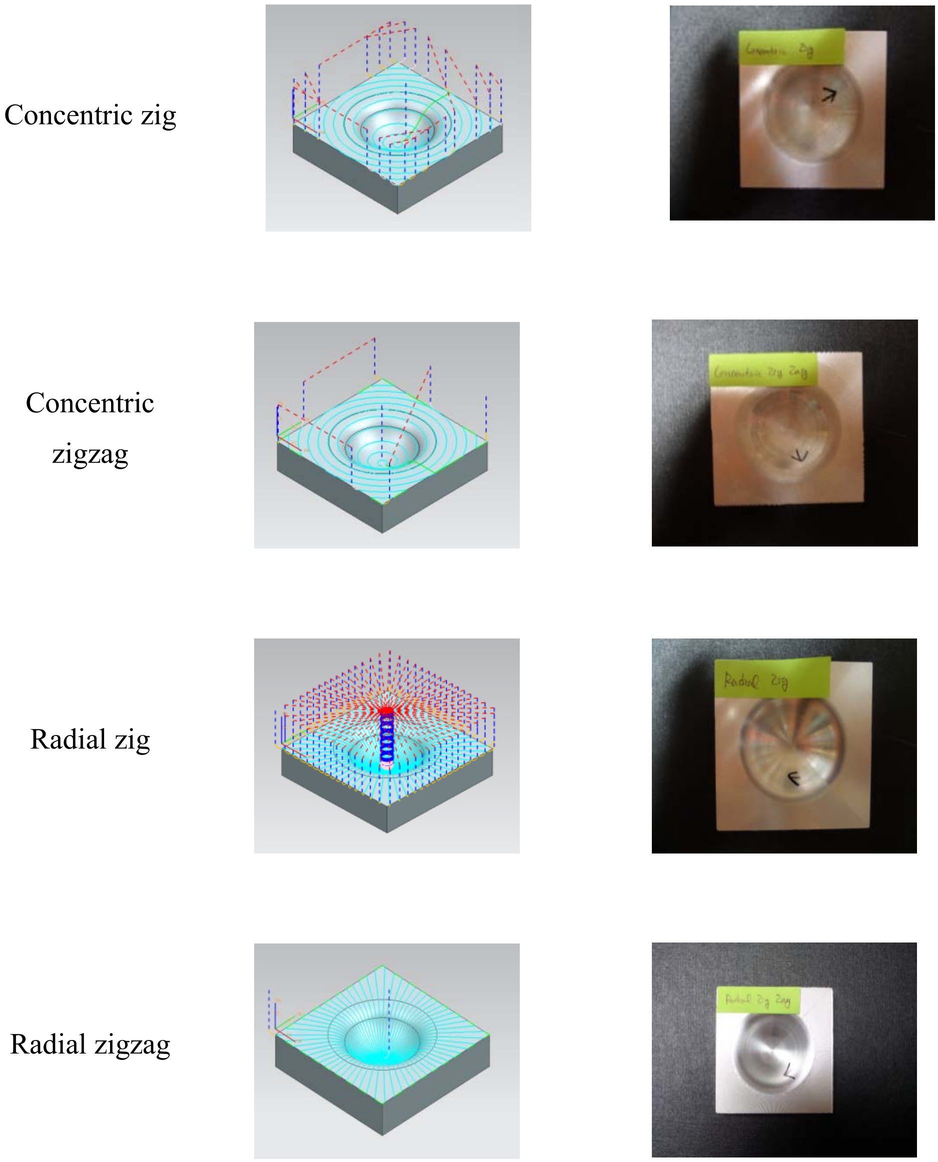


Figure 2. Cutting pattern modeling and machined workpiece

3. Experiment Results and Discussion

3.1. *Surface Roughness and Shape Measurements* The surface roughness was measured at three spots on the flat part of the specimen, among the two parts of the specimen (the flat part and the curved part), and an average value was obtained. Table 3 summarizes the measured surface roughness using the center line average roughness (Ra), the maximum height roughness (Rmax), and the 10-point average roughness (Rz).

To measure the shape, the machined curved part was measured. Table 4 summarizes the values of the measured shape.

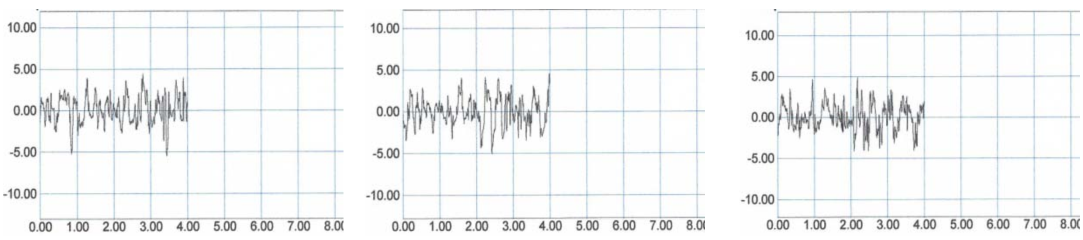
Figure 3 shows the graph of the surface roughness data that measured the flat part machined in a radial zig pattern. Figure 4 shows the graph of the shape measurement data that measured the curved part of the material machined in a radial zigzag pattern

Table 3. Surface roughness results of different flat cutting patterns

Cutting pattern	Surface roughness(μm)		
	Ra	Rmax	Rz
Radial zig	1.32	9.30	8.01
Radial zig zag	1.52	11.00	9.06
Concentric zig zag	1.67	14.03	10.44
Concentric zig	1.91	14.42	11.26
Zig	2.19	15.77	12.71
Zig zag	2.20	14.20	11.70
Follow periphery	2.26	16.33	12.90

Table 4. Contour results for different concave cutting patterns

Cutting pattern	Contour(mm)	Error(mm)
	Radius value	
Radial zig zag	22.61	+0.11
Radial zig	22.12	-0.38
Zig	22.11	-0.39
Follow periphery	22.08	-0.42
Concentric zig	22.03	-0.47
Zig zag	21.86	-0.64
Concentric zig zag	21.47	-1.03

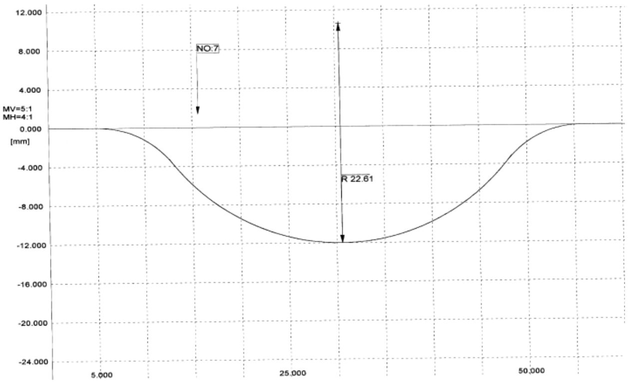


Rmax 9.18(µm) Rmax 8.35(µm) Rmax 10.37(µm)

Rz 7.73(µm) Rz 7.50(µm) Rz 8.81(µm)

Ra 1.34(µm) Ra 1.35(µm) Ra 1.27(µm)

Figure 3. Measured surface roughness characteristics of cutting pattern. (Radial zig).



Radius value	22.61(mm)
Error	+0.11(mm)

Figure 4. Measured contour characteristics of cutting pattern. (Radial zig zag)

3.2. *Discussion*

In the case of the machining using a ball end mill, the tool path is determined using two criteria. One is the increase in the machining efficiency, and the other is the increase in the machining precision. This study considered the machining precision. The cutting patterns that had outstanding surface roughness were the radial zig and the radial zigzag. For the radial zig, Ra = 1.32 μm on the flat part; and for the radial zigzag, Ra = 1.52 μm. Thus, their surface roughness values were superior to those of the other cutting patterns.

The cutting patterns that had an outstanding shape were the radial zigzag and the radial zig. For the radial zigzag, the error was +0.11 mm in the curved part; and for the radial zig, -0.38 mm. Thus, their shape values were superior to those of the other cutting patterns.

The question of which cutting pattern is efficient needs to be answered based on the condition of the production requirements, considering the entire process. Studies on the development of a cutting pattern that can simultaneously satisfy the conflicting requirements of machining efficiency and machining precision are expected to be continuously performed

4. Conclusion

In this study, an experiment was conducted to determine the optimal cutting pattern for the machining of aluminum alloy using a ball end mill, by machining the alloy through the generation of tool paths based on different cutting patterns and by comparing the shapes and surface roughness values of the machined surfaces. The following conclusions are drawn.

1) The measurement of the flat-part surface roughness for each cutting pattern indicated that the radial zig cutting pattern, which applied the zig pattern as a linear cutting pattern that extended from an optimal center point, showed the best machined surface, with a center line average roughness (Ra) of 1.32 μm.

2) The measurement of the curved part shape for each cutting pattern indicated that the radial zigzag cutting pattern, which applied the zigzag pattern as a linear cutting pattern that extended from an optimal center point, showed the best shape, with a concave part shape error of +0.11 mm

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