Analysis of Threshold Angle Variations on The Quality of Finishing Free-form Surface in CNC Milling Process

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A B S T R A C T

The machining process using a combination of steep and shallow strategy is the most widely used strategy for the finishing process on complex models that have many areas of steep walls and shallow floors. Using a single machining strategy on the entire model can lead to long machining times and poor surface finish quality. The steep and shallow strategy can efficiently detect parts of the model that have steep contours and those that have shallow contours. In other words, this strategy can analyze the model surface angle at runtime to identify and divide the machining zone based on the slope angle or commonly called the threshold angle. In this context, the selection of the threshold angle is very important when carrying out the finishing process on free-form surfaces to produce a good surface quality. This study was conducted to determine the optimum threshold angle that can produce the minimum surface roughness between steep areas and shallow areas. Threshold angles that were varied were 20°, 30° and 40°. Machining was carried out using Ballnose type cutting tools with a diameter of 6 mm. Then the stepover and stepdown is 0.1 mm for the finishing process on the surface of the propeller product made of Aluminum by using a CNC Milling machine. From the experimental results, the most optimum threshold angle is at an angle of 40° with an average roughness value in the steep area of 1.9 μm and in the shallow area of 1.3μm and a total average roughness of 1.6μm.

Keywords: CNC, Finishing, Milling, Surface roughness, Steep and shallow, Threshold angle

1. Preliminary

Freeform surface machining is widely used in industry to produce products with complex surface contours, generally using multi-axis CNC milling machines. Industries such as aircraft, shipping, automotive, die and mold, optics, and energy utilize advanced computer aided manufacturing (CAM) systems to produce toolpaths on various product surface shapes.

Due to this high level of machining complexity, technology in CAM systems must take advantage of surface shapes and special algorithms to recognize unique surface characteristics such as curvature, normal vectors, and convex and concave regions. Depending on the level of complexity, the toolpath for the finishing process can be applied to the entire surface of the product or by selecting the boundary contours sequentially.

The quality of the final result of the machining process, especially the finishing process, is usually measured by the level of surface roughness. To meet the demands of productivity and surface quality, proper machining strategies are needed to generate toolpaths, simulate processes, and generate NC codes to be processed on CNC machines to carry out manufacturing processes. Machining using a combination of steep and shallow strategy is the strategy most often used for the finishing process

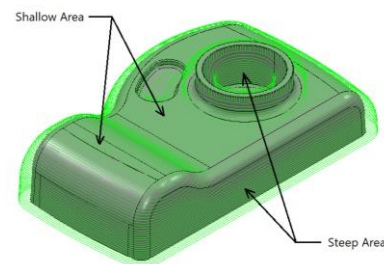on complex models that have many areas of steep walls and shallow floors.

Figure 1. Steep and shallow machining stretegy

Figure 1. shows the shallow area processed using the raster strategy toolpath and the steep area processed using the constant-Z strategy toolpath. The surface slope measured from the horizontal axis which determines the division of the steep area and the shallow area of the contour of a surface is called the threshold angle. The definition of the threshold angle can be seen in the illustration in Figure 2. If the threshold angle is set at an angle of 30°, then the surface of an object with an angle below 30° is considered a shallow area. On the other hand, if the surface of the object has a slope angle above 30°, it is considered a steep area.

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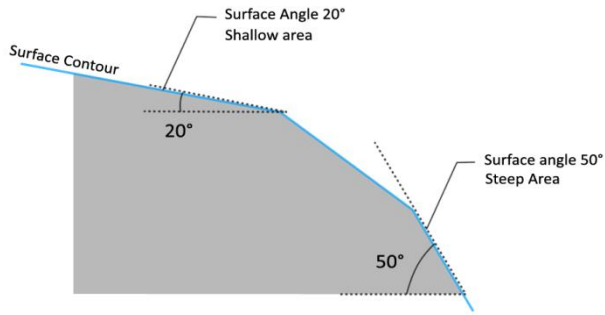
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Figure 2. Threshold Angle 30°

Recent research on Artificial Neural Networks (ANN), can help predict toolpath machining strategies and can be used to determine toolpath strategies or toolpath sequences that show the best results [1]. Analysis of different finishing strategies of a complex geometry consisting of concave and convex surface areas, machining quality can be evaluated through comparison of surface roughness, surface texture and machining parameters [2]. Another interesting study also stated the identification of 3D surface roughness parameters, according to the machining strategy parameters and surface description of objects [3]. Surface topography is also a key element between process parameters and the performance of manufactured objects [4]. Cusp height is mathematically related to the surface roughness parameter [5].

This research was conducted with the aim of determining the ideal threshold angle for the finishing process using the steep and shallow toolpath strategy. Determination of the ideal threshold angle is done by varying the angle of the threshold angle and then experimenting with the machining process on the manufacture of the propeller using a CNC milling machine in each variation. The threshold angle value that produces the minimum average surface roughness in steep and shallow areas is the most optimum threshold angle.
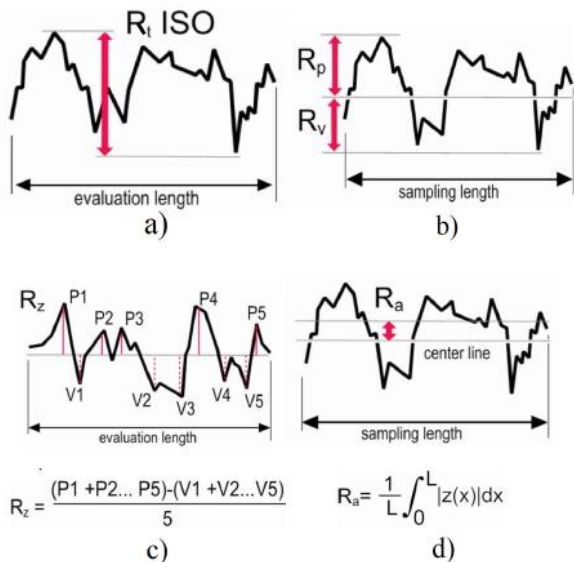

$$R_z = \frac{(P1 + P2 ... P5) - (V1 + V2 ... V5)}{5}$$

$$R_a = \frac{1}{L} \int_0^L |z(x)| dx$$

Figure 3. Surface Rooughness

Many parameters are used to describe surface roughness on a standard basis, such as Rt representing the maximum depth of roughness (Fig. 3a), these parameters are sometimes replaced with Rp and Rv representing, respectively, the height of the highest peak and the depth of the lowest valley with respect to with the mean (Fig. 3b). Rz is another parameter of surface roughness, which can be defined as the sum of the mean of the five lowest valleys and the average of the five highest peaks (Fig. 1c). The parameter that has a significant mathematical effect is Ra, which represents the average arithmetic roughness (Fig. 3d).

2. Research Methods

This research was conducted on the YCM EV 1020 Milling CNC machine. The model used is a 3 blade propeller prototype made of Aluminum as shown in Figure 4. The cutting tool used is a Solid carbide ballnose with a diameter of 6 mm as shown in Figure 5.
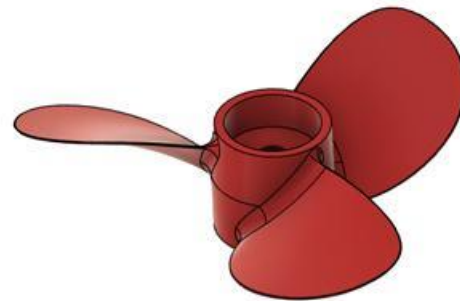

Figure 4. 3D Model of Propeller

Measurement of the surface roughness of the workpiece in this study used the Mitutoyo surftest 301. This tool has an accuracy of 0.01 m. To get good results, the surface roughness measurement is carried out three times on each workpiece surface on each steep and shallow section and then the results are averaged. The direction of the surface roughness measurement is carried out perpendicular to the cutting direction.
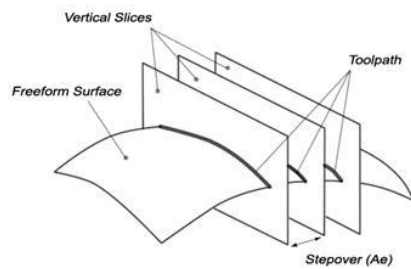

Figure 5. Solid Carbide Ballnose

In this study, the varying threshold angles were 20°, 30°, and 40°. The toolpath finishing strategy used is steep and shallow. Where in steep areas use the constant-Z finishing strategy while in shallow areas use the Raster finishing strategy as shown in Figures 6a and 6b.
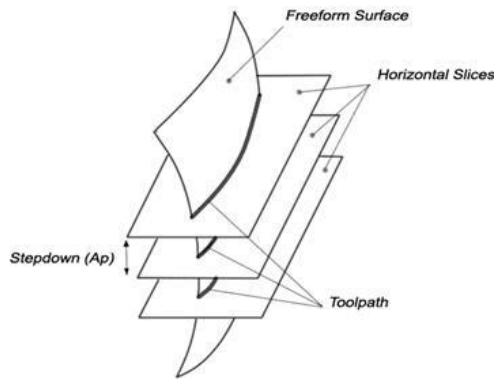
(a)

(b)

Figure 6. (a) Constant-Z finishing Strategy
(b) Raster finishing Strategy

The machining parameters used for the experiments in this study are shown in Table 1. Prior to the finishing process, roughing and semi-finishing processes will be carried out to leave a thickness of 0.2 mm. Then the next step is to carry out the finishing process on the surface of the propeller blade with a steep and shallow strategy with each variation of the threshold angle.

Table 1.Machining Parameters

Area	Steep	Shallow
Strategy	**Constant-Z**	**Raster**
Dia. Cutting tool (mm)	6	
Vc (m/min)	100	
Fz (mm/tooth)	0.1	
Stepover (mm)	-	0.1
Stepdown (mm)	0.1	-

Surface roughness is caused by residual material left or not cut during an incision by the cutting tool. This residual material is commonly referred to as the Cusp height parameter. The relationship between cusp height and surface roughness is obvious, but it is not a simple linear function, and other parameters have significant effects as well [5].
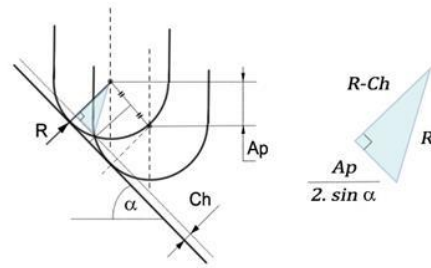

Figure 7. Cusp heigh of Constant-Z Startegy

Cusp height on constant-Z finishing strategy can be seen in Figure 7, its value can be calculated using the following equation [6]:

$$Ch = R - \sqrt{R^2 - \left(\frac{A_p}{2 \cdot \sin\alpha} \right)^2} \qquad (1)$$

Where Ch is the Cusp height, R is the corner radius of the cutting tool, Ap is the stepdown, and α is the angle of the object's surface slope.
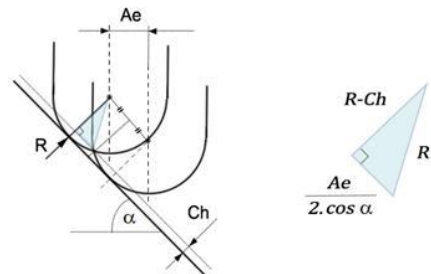

Figure 8. Cusp heigh of Raster Startegy

While the cusp height on the Raster finishing strategy can be seen in Figure 8, its value can be calculated using the following equation:

$$Ch = R - \sqrt{R^2 - \left(\frac{A_e}{2 \cdot \cos\alpha} \right)^2} \qquad (2)$$

Where Ch is the Cusp height, R is the corner radius of the cutting tool, Ae is the stepover, and is the angle of inclination of the surface of the object.

From the above equation, the cusp height value in the steep area and shallow area will be calculated at each varying threshold angle. This value will be compared with the surface roughness value on the surface of the propeller blade as a result of machining.

3. Results And Discussion

The results of the calculation of the cusp height value based on equation 1 and equation 2 for each variation of the threshold angle can be seen in Table 2.

Table 2.Cusp height

Surface angle	Cusp heigh (µm)				
	Threshold angle				
	20°	30°	40°	50°	60°
15°	Sh	Sh	Sh	Sh	Sh
	2.7	2.7	2.7	2.7	2.7
25°	S	Sh	Sh	Sh	Sh
	14	3	3	3	3
35°	S	S	Sh	Sh	Sh
	7.6	7.6	3.7	3.7	3.7
45°	S	S	S	Sh	Sh
	5	5	5	5	5
55°	S	S	S	S	Sh
	3.7	3.7	3.7	3.7	7.6
Average	**6.6**	**4.4**	**3.6**	**3.6**	**4.4**

where:
- sh = shallow area
- s = steep area

The cusp height value is calculated on the surface of the propeller which has a surface slope from 15° to 55°. From the calculation results, the minimum cusp height value is found at the Threshold angle of 40° and 50°, which is 3.6 m.

Cusp height and surface roughness are related, but are not simple linear functions. From the results of the cusp height value in Table 2. it is used as a reference to determine the threshold angle that will be varied for the experiment. Machining experiments have been carried out on the free form surface on the propeller model with the machining parameters set in Table 1.

The surface roughness (Ra) value from the machining experiment results in the propeller finishing process using a steep and shallow strategy with a threshold angle of 20° is shown in Fig. 9. and Table 3.
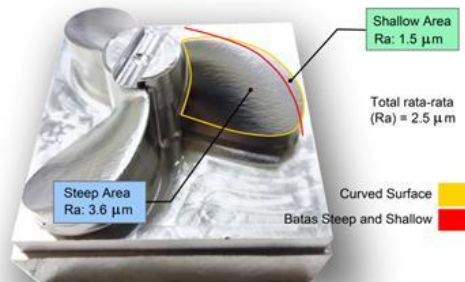

Figure 9. Surface Roughness at Thresold Angle 20°.

Table 3. (Ra) at Threshold Angle 20°

Area	Surface Roughness (Ra) µm			Average
	R1	R2	R3	
Shalow	1.7	1.3	1.6	1.5
Steep	3.1	3.9	3.8	3.6
Total Average				2.5

The surface roughness (Ra) value from the machining experiment at a threshold angle of 30° is shown in Figure 10. and Table 4.
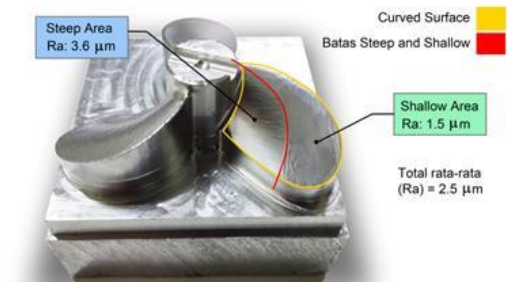

Figure 10. Surface Roughness at Thresold Angle 30°.

Table 4. (Ra) at Threshold Angle 30°

Area	Surface Roughness (Ra) µm			Average
	R1	R2	R3	
Shalow	1.2	1.6	1.4	1.4
Steep	2.7	2.4	2.4	2.5
Total Average				2.0

The last variation is at a threshold angle of 40°, the surface roughness value of the machining results is shown in Figure 11. and Table 5.
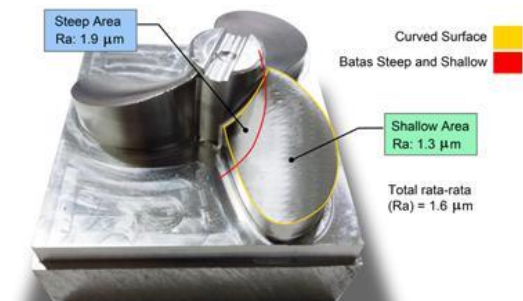

Figure 11. Surface Roughness at Thresold Angle 40°.

Table 5. (Ra) at Threshold Angle 40°

Area	Surface Roughness (Ra) μm			Average
	R1	R2	R3	
Shalow	1.2	1.3	1.4	1.3
Steep	2.1	1.7	2.0	1.9
Total Average				1.6

From the experimental results above, it shows that using a threshold angle of 40° produces the minimum total average surface roughness. The 40° threshold angle setting also produces the minimum average surface roughness in both steep and shallow areas.

Figure 11. Shows the relationship between the value of cusp height and surface roughness (Ra). The smaller the cusp height value, the smaller the surface roughness value.
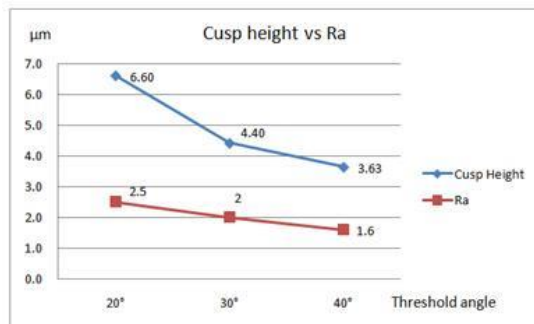

Figure 12. Cusp heigh vs Ra

4. Conclusion

The results showed that the most optimum threshold angel to carry out the finishing process using the steep and shallow strategy was at an angle of 40° with an average roughness value in the steep area of 1.9 m and in the shallow area of 1.3 m and a total average roughness. of 1.6 m. The results of this study also show that there is a relationship between the cusp height value and the surface roughness value.

Acknowledgement

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