# Theoretical and Experimental Study on Surface Finish for Multi-Axis CNC Milling

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**ABSTRACT**

This paper theoretically and experimentally studies the effect of machining parameters on surface finish in 3- and 5-axis CNC milling processes. Based on Z-map method, an analytical model has been proposed to simulate surface finish generated by the milling process. Experiments have been carried out to verify the simulation results. The difference between the simulation and experimental results has been discussed and the reason behind the difference is explored.

**Keywords**: 3-/5-Axis CNC Machining; Simulation; Average Surface Roughness.

## 1 INTRODUCTION

Advancement in manufacturing technology has led to the development of various techniques to improve the manufacturing process. Recently, computer aided manufacturing (CAM) is used to improve the productivity and quality of manufactured product. Complicated products such as dies and molds can easily be manufactured with the help of advanced CAM systems. These products require high quality surface finish. Milling such as end or ball-end milling is extensively used to manufacture and finish these products. Hence, it is of great importance to predict and control products' surface finish during milling process. Most of the currently available commercial CAM software cannot predict the surface finish. The surface generated during milling is affected by different factors such as vibration, spindle run–out, temperature, tool geometry, feed, cross-feed, tool path and other parameters. During finish milling, the depth of cut is small. In this research, the effect of vibration and temperature on surface finish is not considered.

Due to the complexity of end or ball-end milling process, accurate geometric or physical simulation presents certain difficulty. Different researches have been conducted in this regard. To name a few, Kim *et. al*. [1] have used analytical model to calculate the scallop height, which can be used for simple geometry and the situation where cutting tool is normal to the workpiece surface. The mathematical model becomes very complicated for multiple tool pass operation and 5-axis machining. Kang *et. al*. [2] used experiments to determine the effects of inclination angle, up and down milling on the surface finish during ball-end milling. From the experiments, they observed that better surface finish could be obtained for certain inclination angles. Similarly, for 5-axis machining, Kruth and Klewais observed that better surface finish was achieved by tilting the tool in feed direction [3]. Baptista and Simoes [4] experimentally determined that scallop heights in 5-axis CNC with end mill inclined in the feed direction were much smaller than those in 3-axis CNC ball end milling. Although substantial work has been done, in order to predict surface finish, a systematic simulation model is needed. In this study, a simulation system has been developed for 3-and 5-axis CNC milling.

## 2 ANALYTICAL MODEL

### 2.1 Assumptions

For an otherwise complex milling process, certain assumptions are made to analytically model the process. Cutting tool is modeled based on its geometry and shape. The cutting edges are represented by an axial slice of the cutter. Helix angle of the cutter is ignored. The material removed during cutting is equal to the swept volume of the cutter in the workpiece. Effects of tool wear on the surface finish are ignored.Simulation system currently does not consider the effects of vibration. Surface finish is not affected by the initial nature of the flat surface. Surface error caused by deflection of the tool is ignored. These assumptions are used in the simulation model.

### 2.2 Simulation Model

#### Tool Model

A discrete axial slice is assumed to represent a cutting edge. A ball end mill is treated as a tool with semi-circular geometry while a flat end mill is considered as a flat cylindrical surface with fillet at its end. Figure 1 shows the discrete axial slice of a 2-flute ball end mill, where $R$ is the radius of the tool.

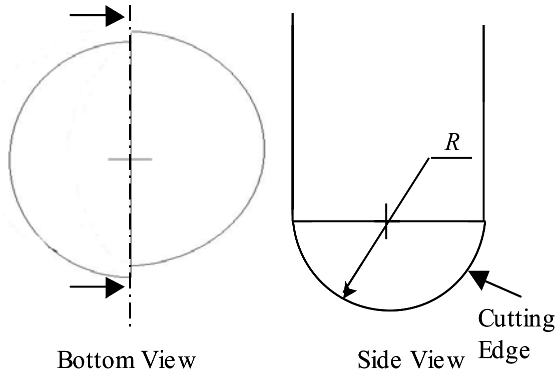



Figure 1 Tool model of a two-flute ball-end mill

**Workpiece Model**

Since the discrete model based simulation technique requires extensive calculations to determine the cut and uncut region, Z-map model based approach was chosen to represent the three-dimensional work-piece. In the Z-map model, the workpiece surface is divided into 2D grid (as shown in Figure 2). The $z_{ij}$ coordinate of each grid point represents the height of the workpiece at that location, which changes with the cutting process. The $z_{ij}$ coordinates are also associated with $x_i$ and $y_j$ coordinates of grid points and can be expressed as a function of $f(x_i, y_j)$.

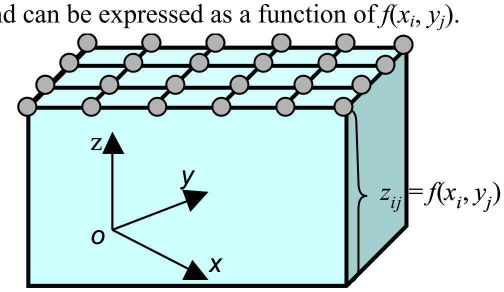



Figure 2 Z-map representation of workpiece

**Tool Motion Modeling**

The tool motion has two components: rotation and translation i.e., tool rotates with spindle and in the meantime translates with feed. Figure 3 shows the motion of the tool. Translation motion is assigned to the center point of the tool. The movement of the center of the tool will be controlled by the CNC program. In Figure 3, the 2-flute tool has two cutting edges 180$^o$ apart. The points on the cutter are mapped with respect to the center of the tool so that all the intersection calculations can be carried out based on the center position of the tool. The tool and workpiece intersection points are calculated based upon their interference. The workpiece material, which occupies the overlapped space between the the tool and workpiece, will be removed by machining. When the material is removed, the workpiece surface is updated. The $z$ coordinates of grid points on the new surface are updated accordingly. These new $z$ coordinates, thus obtained after carrying out simulations, contains the information of the machined surface topography generated by the milling process.

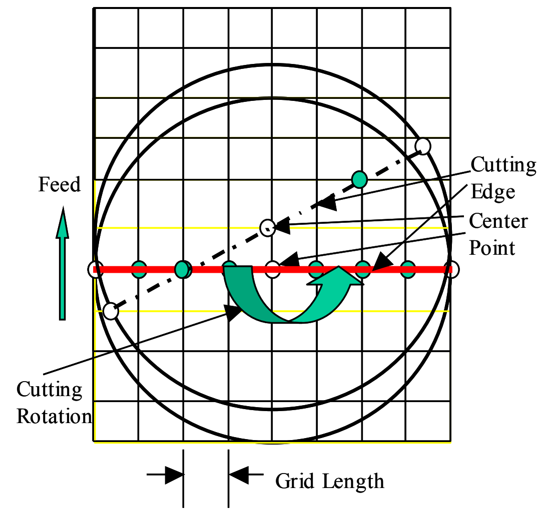



Figure 3 Tool discrete Motion

There are various parameters to represent the surface finish. In this research, spatial average surface roughness has been chosen as the parameter to represent the surface finish. The spatial average surface roughness calculation was based on the method suggested by Dong et. al. [5].With VC++ (MFC) and OpenGL, a generalized simulation system was developed. Basic information such as type of tool, tool diameter, inclination angle and workpiece size and mesh size can be input to the simulation system through user interface. The simulation results are affected by the selection of mesh size and discrete incremental angle.

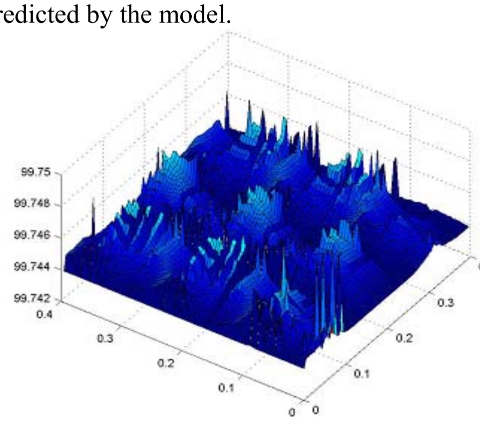
## 3 EXPERIEMENT SETUP

The verification experiments have been conducted on Mori Seiki 5-axis (GV503/5Ax) and 3-axis (CV500) CNC machines. The average surface roughness of machined workpieces were measured by Zygo New View 5000. Ball end mills of Φ6mm (2 flutes), Φ10mm (2 flutes) and Φ6.25mm (3 flutes) were used. Corresponding to the simulation, different feeds, pick feeds, spindle speeds and inclination angles were adopted to study the effect of these machining parameters. The CNC code was generated by using Feature CAM or a software program specifically written by the authors for various inclination angles. The workpiece materials used were aluminum and case hardened steel. Coolant was applied during machining

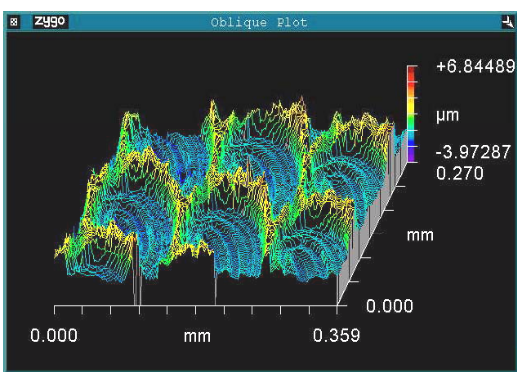
## 4 RESULTS AND DISCUSSIONS

### 4.1 Surface Topography

With the current model, the surface topography of milled workpiece can be simulated. Figure 4(a) shows the simulated surface topography. Compared to the measured result (Figure 4(b)), we can see that the current model has described the basic characteristics of milled surface. Due to the tool shape of ball end mill and cross feed, scallops are formed on workpiece surface during milling. Comparing these two figures, we can see that the scallop characteristics such as distribution on surface have been obtained by the current model. The calculated and measured heights largely agree with each other, except for a few variations on the measured surface. The difference may be due to material plastic deformation, which cannot be predicted by the model.




(a) Simulated surface Topography




(b) Measured surface topography

Figure 4 Surface topography

### 4.2 Surface Roughness

The preliminary tests were carried on a 3-axis machine tool, Mori Seiki CV500. The cutting tool used was 3-flute high speed steel ball end mill with a radius of 3.175 mm. The workpiece material was aluminum. Figure 5 shows the simulation and experimental results for surface roughness. The simulation results show that surface roughness increases with the increase of feed rate, which agrees with the experimental results. For 3-axis machining, the difference between the predicted experimental results for surface roughness is pretty large. This may attribute to the vibration and spindle run-out in real machining, which were not considered in the simulation. The experiment has shown that higher cutting speed improves surface finish. Comparing the two simulation results under the same machining conditions but different discrete incremental angles, we can see that smaller incremental angle brings the simulated result closer to the experimental one.

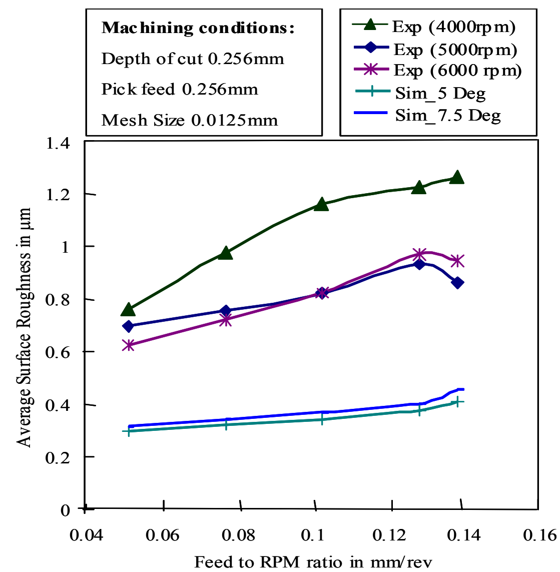



Figure 5 Simulation and experimental result for 3-axis machine

Further experiments were carried out on 5-axis machine tool, Mori Seiki GV503. These experiments were carried out by using 2-flute carbide coated ball end mill with a radius of 3mm. Spindle speed was maintained at 7000 rpm. The workpiece material was case hardened. In the simulation, 10-degree discrete incremental angle was used. The simulated and experimental results are compared in the Figure 6. The simulation has predicted the increase trend of surface roughness with the increase of feed rate. Compared to the above result by 3-axis machine, the current model predicts surface roughness by 5-axis machine better.

The simulation model was also applied to simulate the 5-axis machining, in which the cutting tool was inclined to workpiece surface cross feed directions. Figure 7 shows the effect of inclination angle in cross feed direction on surface roughness. The simulation result agrees with the average trend of the experimental result.

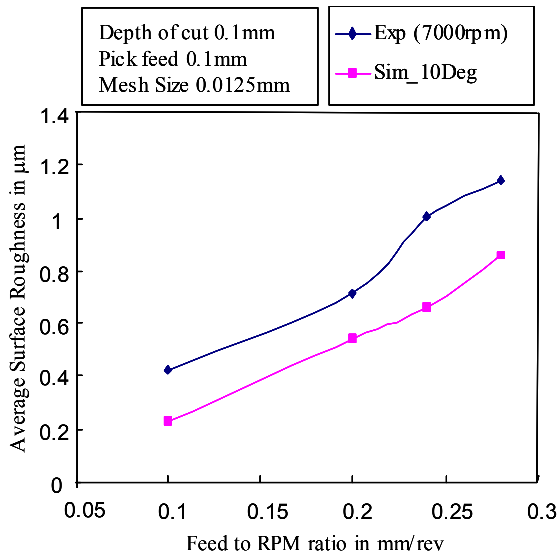



Figure 6 Simulation and experimental result for 3-axis machining on 5-axis machine

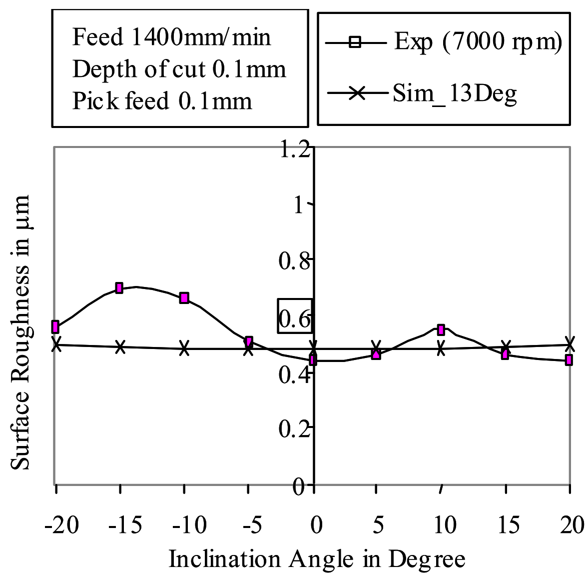



Figure 7 Surface roughness for 5-axis machining with inclination angle in cross feed direction

## 5 CONCLUSIONS

A simulation model based on Z-map method has been developed to calculated surface finish generated by 3- and 5-axis CNC machining. In order to verify the effectiveness of the model, machining experiments have been conducted under different conditions. This model has successfully predicted the surface topography, especially the scallop in CNC milling. The prediction for surface roughness largely agrees with the experimental results. The difference between the simulation and experiment may attribute to the effects of vibration, spindle run-out and workpiece material property in actual machining.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