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# Optimizing cutting parameters in inclined end milling for minimum surface residual stress – Taguchi approach

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ABSTRACT

End milling is an important and common machining operation because of its versatility and capability to produce various profiles and curved surfaces. Inclined end milling possesses the capability to translate in all 3 axes but can perform the cutting operation in only 2 of the 3 axes at a time. This research work focuses on investigating the effect of machined surface inclination angle, axial depth of cut, spindle speed and feed rate for better surface integrity in inclined end milling process utilizing titanium coated carbide ball end mill. An optimization method known as Taguchi optimization was used in order to identify the main factors that cause the greatest variation and to determine control parameters in the least variability. Data analysis was conducted using signal-to-noise (S/N) response analysis and analysis of variance (Pareto ANOVA). The optimum condition results obtained through analysis show improvements in residual stress and microhardness in inclined end milling process.



## 1. Introduction

Milling is a machining process of removing material by the relative motion between a workpiece and rotating cutter with multiple cutting edges. It is an interrupted cutting operation in which the teeth of the milling cutter enter and exit the workpiece during each revolution. With 2.5D cutting in milling it is possible to perform point-to-point, contouring and pocketing operations [1]. 2.5D is similar to 3D machining in that it can translate in all 3 axes but has a limitation of only being able to perform in 2 of the 3 axes at a time or on the same plane that coincides with one of the milling machine planes. During operation, the depth of cut remains constant and the cutter movement only interpolates 2 axes simultaneously, meaning that the cutter moves only on the main planes XY, YZ and ZX and then moves to the next depth and repeats the same movement. A terrace-like approximation of the required shape is produced in the roughing process in order to remove excess material. Once roughing is done, finishing is used to transform the part into its final design shape with acceptable tolerance [2]. Previously, research has been done on 2.5D cutting, regarding for instance, the efficiency of the cutting path in 2.5D cutting of pocket milling [3,4], developing a generic algorithm for a cutter engagement function in 2.5D milling [5], cutting tool sizes for a 2.5D pocket [6], etc. However, there is still a lack of research on product surface integrity after being machined in 2.5D cutting.

The surface integrity after machining process correlates very closely with the cutting parameters [7,8] and the tool geometries [9]. If the cutting conditions are not selected properly, the process may result in violations of machine limitations and part quality or reduced productivity. Therefore, it is important to understand the relationship

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between the cutting conditions and the surface integrity of the machined part, such as the microhardness and residual stress of the machined surface due to the effects on product appearance, performance, and reliability.

Previous researches have shown that microhardness is greatest when it is near the surface layer but however decreases rapidly as the depth increases. The microhardness gradually increased with increase depth below the machined surface caused by the annealing of the workpiece during machining causing softening close to the finished surface. They also found out that microhardness measurement of Al and Al/SiC did not indicate significant subsurface modifications [10]. Axinte and Dewes [11] also found that there are no significant changes in microhardness with depth below the machined surface. However, both researches have no concrete reason why do these occur. Kalvoda et al. [12] shows that there are some differences in microhardness. However, there is no pattern of changes in their results since they only measured the microhardness at a depth of cut of 0.4 mm. They also indicate that based on the measurement of acceleration, a higher magnitude of the microhardness could be caused by the ploughing effect during the machining process.

Residual stresses develop during most manufacturing processes involving material deformation, heat treatment, machining or processing operations that transform the shape or change the properties of a material. The presence of residual stresses in components has been known to be one of the major factors affecting their end performance. The mechanical loading (e.g. cutting force) generally introduces compressive stresses due to contact pressure, whereas thermal loading is generally associated with tensile stresses [13]. Thermal and mechanical loads that occur during milling process generally will influence the surface integrity of the machined surface. The thermal load are caused by the friction in the milling process which will leads to tensile residual stress and reduced the compressive residual stresses in the substrate. However, the mechanical load will induced high compressive residual stress [14]. In machining, residual stresses are closely related to the cutting parameters used during machining. Higher depth of cut and feed rate exhibited detrimental effects by generating higher stresses [15]. Increasing cutting speed and feed per tooth causes compressive stress to decrease, probably due to a higher thermal effect on the workpiece surface [11].

In line with the literature above, to optimize the cutting parameters for better surface integrity in inclined end milling cutting, this study was conducted by anticipating spindle speed, feed rate, depth of cut, and machined surface inclination angle as control variables. The main objective of this research work is to find the best combination of parameters in inclined end milling of carbon steel workpieces utilizing a titanium-coated carbide ball end mill to obtain higher surface hardness and lower residual stress.

## 2. Experimental work

### 2.1. Design of experiment

In this research, Taguchi optimization method is used. It is an optimization method that includes planning, conducting and analyzing the results of matrix experiments in order to achieve the best control factor levels [16]. The best control factor levels are those that maximize the signal-to-noise ratios (S/N), which are log functions of desired output, serve as objective functions for optimization, and help with data analysis and optimum result prediction. Wide research has been done on optimization method especially Taguchi method and it has been proven that with a minimum number of experiments it can improves process performance [17,18]. The control factors selected are machined surface inclination angle ($\theta°$) (Factor A), axial depth of cut (mm) (Factor B), spindle speed ($min^{-1}$) (Factor C) and feed rate (mm/min) (Factor D). With four control factors at three levels each, the standardized orthogonal array $L_9$ ($3^4$) was selected. The levels of Factor A, and B, were chosen based on the result in preliminary experiment, while, both of the Factor C and D levels were selected based on the tool manufacturer's recommendation. The nine experiments with the details of combinations for each control factor (A–D) are shown in Table 1.

### 2.2. Experimental setup

The experimental setup used in this research is shown in Fig. 1. The machine used is a 5-axis CNC machining center (SPINNER U-620) built with Siemens controller. The machine is designed for highest precision with table size $500 \times 500 \times 500$ mm, maximum spindle speed of 12,000 $min^{-1}$ and 32 tool changes. The tools used in the experiments are 4 flutes, 10 mm diameter titanium coated carbide with flat end mill and ball-nose end mill. The workpiece material is S50C Medium Carbon Steel which has carbon content in between 0.3% and 0.55% carbon. The experimental test was conducted in flood condition to provide better cooling, increased tool life, reduced friction, and also improved machined surface finish.

The end milling was conducted in roughing and finishing process. The first cutting stage is a rough cutting to remove the excess material using a 10 mm-diameter titanium-coated carbide flat end mill. A stairs step inclined plane was produced at different angles to complete rough cutting to prepare the stairs step inclined plane, as shown in Fig. 2a. The second cutting stage was finish cutting to produce a flat, smooth, inclined surface to investigate the influence of machined surface inclination angle on surface integrity in inclined end milling. In this cutting stage the end mill tool used was 10 mm-diameter titanium-coated

**Table 1**
$L_9(3^4)$ Orthogonal array.

| No. | $A$ ($\theta°$) | $B$ (mm) | $C$ ($min^{-1}$) | $D$ (mm/min) |
|---|---|---|---|---|
| 1 | 100 | 0.1 | 3200 | 870 |
| 2 | 100 | 0.25 | 3700 | 920 |
| 3 | 100 | 0.5 | 4200 | 970 |
| 4 | 110 | 0.1 | 3700 | 970 |
| 5 | 110 | 0.25 | 4200 | 870 |
| 6 | 110 | 0.5 | 3200 | 920 |
| 7 | 120 | 0.1 | 4200 | 920 |
| 8 | 120 | 0.25 | 3200 | 970 |
| 9 | 120 | 0.5 | 3700 | 870 |