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 × 500 × 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

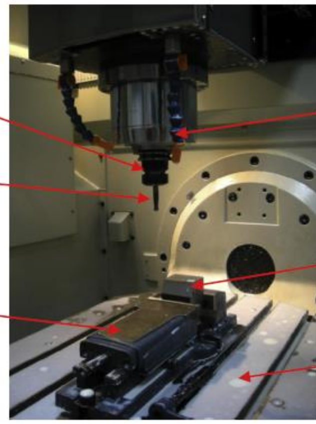

Fig. 1. Experimental set-up.

carbide ball-nose end mill. The tool moved on the previously machined rough surface to produce a flat, smooth, machined surface with different inclination angles and different axial depths of cut, as shown in Fig. 2b.

To measure the machined surface microhardness, an HMV Micro Hardness Tester was used, with 1.961 N load, HV = 0.2 and 10 s indentation time. The microstructure of the machined surfaces was observed with a Philips Scanning Electron Microscope (SEM) XL40. The SEM settings used were acceleration voltage of 10 kV, 5.0 spot, 1000× magnification, secondary detector and 6.0 WD. The residual stress on the machined surface inclination angle was measured using X-ray diffraction (XRD) machine. Diffraction occurs at an angle of 2θ, defined by Bragg's Law as $n\lambda = 2d\sin\theta$, where n is an integer denoting the order of diffraction, λ is the X-ray wavelength, d is the lattice spacing of crystal planes and θ is the diffraction angle. The strain in the crystal lattice is measured and the residual stress producing the strain is calculated. The presence of a tensile stress in the sample results in Poisson's ratio contraction, reducing the lattice spacing and slightly increasing the diffraction angle, 2θ. If the sample is then rotated through some known angle ψ, the tensile stress present in the surface increases the lattice spacing over the stress-free state and decreases 2θ. Measuring the change in angular position of the diffraction peak for at least two orientations of the sample defined by angle ψ enables the calculation of the stress present in the sample surface lying in the plane of diffraction, which contains the incident and diffracted X-ray beam [19]. In this research, the stresses were measured parallel and perpendicular to the feed direction. The X-ray diffraction (XRD) machine was equipped with Cu Kα target with a tube voltage of 45 kV and current of 30 mA. The peak 2θ was set 116.5°. A number of XRD measurements were made at different tilts (ψ). In this experiment, the psi (ψ) tilting angles were set at 0°, 12.9°, 18.4°, 22.8°, 26.6°, 30.0° and 33.2°. The phi (ϕ) angles were set at 0° and 90°.

The most common method to determine stress is $\sin^2\psi$. By resolving the angular peak shift and applying Bragg's

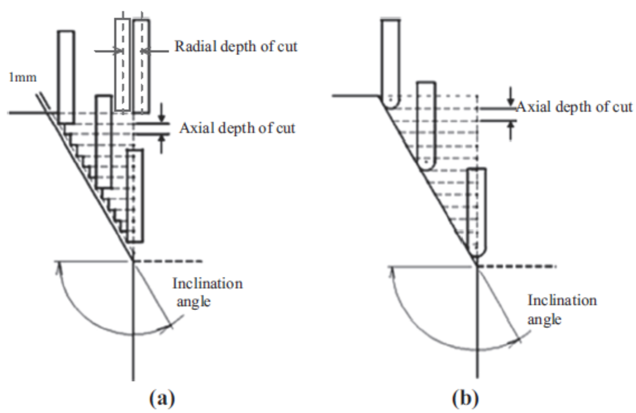

Fig. 2. Machining processes.

law to quantify the *d*-spacing, residual stress on the machined surface can be calculated using the theory of linear elasticity. The inter-planar spacing, *d*, is measured and plotted versus $\sin^2\psi$. The stress can then be calculated from such a plot by calculating the gradient of the line and with basic knowledge of the elastic properties of the material. By finding *m*, the gradient of the *d* vs. $\sin^2\psi$ curve, the stress can be calculated using Eq. (1).

$$\sigma_\phi = \left(\frac{E}{1+v}\right)m \quad (1)$$

This formula is derived from Fitzpatrick et al. [20].

3. Experimental results, analysis and discussion

3.1. Experimental results

The finish cutting process is carried out using a ball-nose end mill to produce a flat, smooth, inclined surface to investigate the influence of machined surface inclination angle on the surface integrity in inclined end milling. The calculated S/N ratio for microhardness and residual stress are shown in Table 2. The S/N ratios transform several repetitions into one value which indicates the amount of variation present and the shift of mean response in order to identify the control factors that may reduce variation and improve quality. The method for calculating the S/N ratio depends on the characteristic type, whether smaller is better, larger is better or nominal is better. In the case of microhardness, larger values are preferred; meanwhile, for residual stresses smaller values are preferred, as they indicate compressive residual stress. The equations for calculating the S/N ratio with larger is better and smaller is better are as follows:

Larger-is-better

$$S/N_i = -10\log\left(1/n\sum_{j=1}^{n}1/y_j^2\right) \quad (2)$$

Smaller-is-better

$$S/N_i = -10\log\left(1/n\sum_{j=1}^{n}y_j^2\right) \quad (3)$$

where y_i is the individual measured microhardness or residual stress and *n* is the number of repetitions. The degree of predictable performance of a process in the presence of noise factors could be defined from S/N ratios, whereby for each factor, the higher the S/N ratio the better the result.

Table 2
Results of S/N ratios for microhardness and residual stress.

Exp No	Microhardness	Residual stress	
		Feed direction	Cutting direction
	S/N (dB)	S/N (dB)	S/N (dB)
1	48.4514	−56.2273	−56.1861
2	47.7549	−58.6666	−54.2426
3	47.6005	−51.8041	−62.1076
4	49.1667	−51.0514	−58.7981
5	47.8303	−63.3554	−56.8157
6	47.7656	−52.8233	−59.2685
7	49.1369	−63.9985	−56.1861
8	48.2125	−63.2595	−56.8157
9	47.5920	−63.6369	−63.1440

3.2. Data analysis and discussion

3.2.1. Microhardness

The S/N response data are calculated using Minitab17 software (trial version). The largest S/N response would reflect the best response which results in the lowest noise for microhardness and residual stress. These are the criteria employed in this study to determine the optimal machining parameters. The main effects plot of SN ratios for selecting the best combination levels for maximum microhardness is shown in Fig. 3. The highest machined surface inclination angle (A3, 120°), with, lower axial depth of cut (B1, 0.1 mm), higher spindle speed (C3, 4200 min^{-1}) and higher feed rate (D3, 970 mm min^{-1}) are determined to be the best choices for obtaining the highest microhardness value. Therefore, the optimal parameters are set as $A_3B_1C_3D_3$.

Pareto ANOVA is an alternative way to analyze data for process optimization. This method enables the significance of factors and interactions to be evaluated through Pareto-type analysis. It also facilitates obtaining the optimal factor levels. Table 3 shows the Pareto ANOVA for microhardness using the S/N response data from Table 2. The summation of squares of differences (*S*) for each control factor is calculated such that for example, S_A can be obtained with the following equation:

$$S_A = (A_1 - A_2)^2 + (A_1 - A_3)^2 + (A_2 - A_3)^2 \quad (4)$$

Similarly, S_B, S_C and S_D are calculated. The contribution ratio for each factor is calculated as the percentage of summation of squares of differences for each factor to the total summation of the squares of differences. A Pareto diagram is plotted using the contribution ratio and cumulative contribution. The best factor combination levels for maximum microhardness, as shown in Table 3, are found as: the axial depth of cut (B) which contributes 85.0%, followed by, machined surface inclination angle (A) 8.0%, feed rate (D) 6.9%, and spindle speed (C) 0.1%.

Result analysis done using signal-to-noise (S/N) response analysis and Pareto ANOVA shows similar results. Axial depth of cut (Factor B) was found to be the most significant factor affecting microhardness, followed by machined surface inclination angle (Factor A), feed rate (Factor D), and spindle speed (Factor C). A lower axial depth of cut demonstrated an increase in microhardness. By further decreasing axial depth of cut, the number of cutting paths increased, as seen in Fig. 4. The machined surface thermally induced at every cutting path and by increasing the number of cutting paths, rapid workpiece heating occurred, resulting in increased hardening. As the machined surface inclination angle increased, the contact area between the tool and machined surface increased, causing more material to be removed during machining. In combination with higher speed and feed rate the heat generated during machining increased, hence increasing

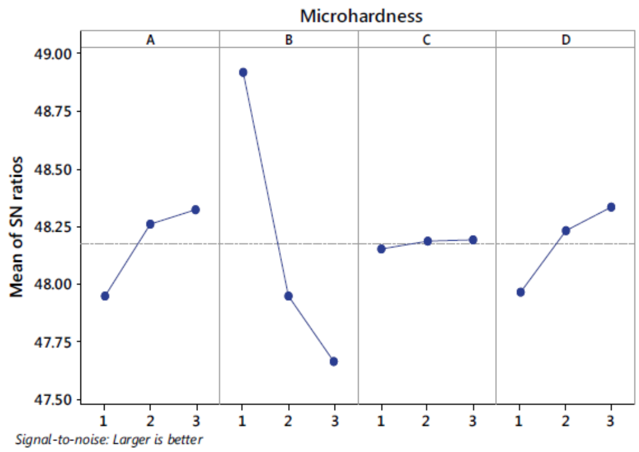

Fig. 3. Main effects plot of SN ratios for microhardness.

Table 3
Pareto ANOVA analysis for microhardness.

Level of input parameters (i)	S/N response data (dB)			
	A_i	B_i	C_i	D_i
Level 1 (i = 1)	143.8067	146.7550	144.4295	143.8736
Level 2 (i = 2)	144.7626	143.7977	144.5136	144.6574
Level 3 (i = 3)	144.9414	142.9581	144.5676	144.9797
Total of summation	433.5107	433.5107	433.5107	433.5107
Sum of squares of differences (S)	2.2332	23.8672	0.0291	1.9415
Total summation of squares of differences $S_t = S_A + S_B + S_C + S_D$	28.0710			
Contribution ratio (%)	8.0	85.0	0.1	6.9
Cumulative contribution ratio (%)	85.0	93.0	99.9	100.0
Factor	B	A	D	C
Optimum combination of significant factor levels	$A_3B_1C_3D_3$			

the temperature and plastic flow, resulting in greater hardening. A competing process between work hardening and thermal softening took place that affected the fundamental behavior of the workpiece material [21]. The instability in the form of plastic deformation due to high temperature in high speed machining led to softening of the machined surfaces [22]. Sufficient coolant between the tool and machined surface caused the softened machined surface to harden due to the subsequent rapid cooling. Increasing the machined surface inclination angle allowed the access of more coolant to the tool-machined surface interface.

3.2.2. Residual stress

The main effects plot of SN ratios for selecting the best combination levels for minimum residual stress in the feed direction is shown in Fig. 5. Based on the criteria of higher SN ratio, the lowest machined surface inclination angle (A1, 100°) with higher axial depth of cut (B3, 0.5 mm), lower spindle speed (C1, 3200 min^{-1}) and higher feed rate (D3, 970 mm min^{-1}) are determined to be the best choices for obtaining the lowest value of residual stress in the feed direction. Therefore, the optimal parameters are set as $A_1B_3C_1D_3$.

The main effects plot of SN ratios for selecting the best combination levels for minimum residual stress in the cutting direction is shown in Fig. 6. Based on the criteria of higher SN ratio, the lowest machined surface inclination angle (A1, 100°) with moderate axial depth of cut (B2, 0.25 mm), lower spindle speed (C1, 3200 min^{-1}) and moderate feed rate (D2, 920 mm min^{-1}) are determined to be the best choices for obtaining the lowest value of residual stress in the cutting direction. Therefore, the optimal parameters are set as $A_1B_2C_1D_2$.

The Pareto ANOVA analysis for residual stress in feed and cutting directions using the S/N response data from Table 2 are shown in Tables 4 and 5. The best factor combination levels for minimum residual stress in the feed direction are found as: the machined surface inclination angle (A) 53.0%, axial depth of cut (B) 22.9%, feed rate (D) 20.4%, and finally, spindle speed (C) 3.8%. Meanwhile, the best factor combination levels for minimum residual stress in the cutting direction are found as: the axial depth of cut (B) 75.3%, feed rate (D) 17.5%, spindle speed (C) 4.0%, and machined surface inclination angle (A) 3.3%. The Pareto ANOVA analysis additionally facilitated the determination of $A_1B_3C_1D_3$ as the best for the lowest value of residual stress in the feed direction; and $A_1B_2C_1D_2$ is best for the

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