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Exploring the Influence of Machining Parameters on Geometric Form and Orientation Controls (2^3 Design)

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Abstract

This work explores the influence of machining parameters using on geometric form controls flatness and straightness as well as orientation control parallelism using an aluminum 6061 workpiece. Due to its good strength, machinability and cost- effectiveness, aluminum 6061 is widely used. In this experimental work, full factorial design is used and each factor has two levels. The response parameters chosen include flatness, straightness, and parallelism, which govern the form and orientation control of geometric dimensioning and tolerancing (GD&T). Different values of machining parameters spindle speed, feed and depth of cut take as per the design matrix of the 2^3 full factorial design. To find out the relative significance of the input factors, an analysis of variance (ANOVA) was conducted. Influence of individual effect and interaction effect of machining parameters on response flatness, straightness, and parallelism was studied. Mathematical modeling can assist in selecting optimal process parameters. Flatness, straightness, and parallelism were measured using a coordinate measuring machine. The model's predicted and the experimental values were seen to agree very well. This research examines how the shape of the geometry and orientation control of produced components are affected by machining factors, including cutting speed, feed rate, depth of cut, tool substance, and machine stiffness. The study looks at how these characteristics affect properties like surface quality, dimensional accuracy, and geometric deviations in the finished product by methodically changing them. This work strives to determine the ideal machining settings for reducing form errors and guaranteeing constant component orientation using both experimental and analytical methods. Particularly for intricate, precision-critical applications, the results offer significant insights for the design and optimization of machining processes, promising improved production quality and efficiency.

Keywords: Speed, feed, depth of cut, flatness, straightness, parallelism, analysis of variance

INTRODUCTION

The geometric dimensioning and tolerancing (GD&T) concept emphasizes the integration of various functions in a manufacturing organization. It could be a symbolic language used by engineers and producers to describe items and facilitate communication between entities that co-produce the product. The language can also be utilized for essential communication of accurate portion designs and their proper execution. GD&T was made to ensure proper get-together of mating parts, improve quality, and reduce rework and related costs [1, 2]. Flatness controls are regularly utilized on surfaces that can rest on a planar surface without moving forward and in reverse significantly. Geometric control can be confirmed by dial pointer, coordinate measuring machine (CMM), or other strategies [3]. In this work, the measurement control uses a CMM.

Amit Joshi and colleagues utilized the Taguchi method to investigate the effects of various parameters on the surface finish of aluminum cast

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heat treatable alloy during end milling. By varying machining parameters they analyzed the effect on the response. Their variance examination results indicate that the feed rate is the primary influencing factor in modelling surface finish [4]. Bajic and colleagues explored how face milling's depth of cut, feed rate, and cutting speed affected the degree of surface roughness. They employed regression analysis and neural networks to predict surface roughness based on experimentally determined data [5, 6]. Patel and team explored the influence of material removal rate (MRR) during the flashing operation of precision steel ball fabrication using a 2^3-replicate experimental design. They developed a model based on fuzzy logic [7, 8]. Schmitz and colleagues explore comprehensive understanding of thermal, cutting force error is essential for improving the accuracy of high-speed milling. Their study emphasizes the importance of addressing thermal management, improving tool material and design, and enhancing machine tool calibration to reduce errors and improve overall machining operations [9]. Woo and coauthors examined high-speed cutting characteristics using the design of experiments [10]. Abdelilah et al. discussed the selection of cutting tools during milling operations [11].

Research Novelty and Managerial Implications

By conducting the research across different materials (metals, polymers, composites) and understanding how machining parameters affect geometric form and orientation controls, manufacturers may raise the norms and consistency of their goods by more accurately managing the machining situations. The rest of the article is structured as follows: second section: Experimentation; third section: Analysis of Variance; fourth section: Regression Model; and final section: Conclusion.

EXPERIMENTS AND METHODOLOGY

Selection of Workpiece Material, Machine and Cutting Tools

The test work piece material is Al6061. Its typical composition along with its few mechanical properties are shown in Table 1. It is the most widely used material due to its less cost. Machinability tests were carried out on the vertical machining center (VMC 430).

Experimental Procedure, Measuring Techniques, and Results

Experimental trials were conducted on aluminum blocks measuring 50 mm × 50 mm × 40 mm. Spindle speed, feed, and depth of cut had been selected as input factors, while geometric shape and orientation controls were taken onto account as a response.

The levels of these input variables are detailed in Table 2 and illustrated in Figure 1. The aluminum workpiece block was securely clamped using a hydraulic vice. Initial machining was performed on all sides of the block before the face milling process was executed on each face. Measurement data for flatness, straightness, and depth of cut were obtained using a hexagon coordinate measuring machine (CMM).

Table 1. Component composition and mechanical properties of Al6061.

Components	Chemical Composition %
Magnesium	0.811.2
Silicon	0.4–0.8
Iron	Max. 0.7
Copper	0.15–0.40
Titanium	Max. 0.25
Manganese	Max. 0.15
Chromium	Max. 0.15
Others	0.04–0.35
Aluminum	Remainder
Mechanical properties	
Ultimate tensile strength	310 MPa
Yield strength	275 MPa

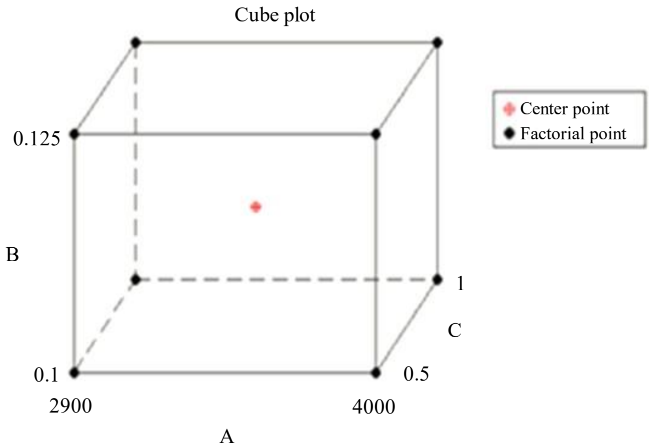

Figure 1. Factors and levels.

Table 2. Factors and levels.

Factors	Coded factors	Low level (–)	High level (+)	Center points
Spindle speed (rpm)	A	2900	4000	3450
Feed (mm/min)	B	0.1	0.125	0.1125
Depth of cut (mm)	C	0.5	1.0	0.75

Table 3. Experimental data for different treatment combinations.

Labels	A	B	C	Flatness	Straightness	Parallelism
1	–	–	–	0.001	0.001	0.002
a	+	–	–	0.003	0.003	0.001
b	–	+	–	0.001	0.001	0.003
ab	+	+	–	0.001	0.003	0.001
c	–	–	+	0.003	0.001	0.005
ac	+	–	+	0.004	0.003	0.004
bc	–	+	+	0.001	0.002	0.002
abc	+	+	+	0.002	0.003	0.015
Center points	0	0	0	0.007	0.004	0.121
	0	0	0	0.002	0.003	0.115
	0	0	0	0.002	0.002	0.115
	0	0	0	0.003	0.004	0.112

Carbide inserts with a 32 mm diameter were utilized for machining the workpieces, and a 4 mm probe diameter was employed in the hexagon CMM. Table 3 presents the responses corresponding to coded factors and treatment combinations utilizing the 2^3 full factorial design with four center points [12].

ANALYSIS OF VARIANCE STUDY

To identify significant factor, individual factor effect on response analysis of variance (ANOVA) was performed. In a factorial experimental design is used to explore influence of main and interaction effect of independent variables on dependent variables. Tables 4–6 show the ANOVA table for flatness, straightness, and parallelism, respectively.

Analysis of Variance for Flatness, Straightness, and Parallelism

Keeping track of flatness, straightness, and parallelism is necessary for maintaining quality in manufacturing. All three factors are key to ensuring that parts fit together properly and work as intended. Flatness is about how well a surface matches a perfect plane, making sure it is uniform across its entire area. Straightness checks how closely a line acting as an edge follows a straight path without buckling. Parallelism ensures that two surfaces stay equally spaced and aligned along their entire length.

Table 4. Analysis of variance (ANOVA) table: flatness.

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*
Main effects	3	0.00000850	0.00000850	0.00000283	0.50	0.708
2-way interaction	3	0.00000100	0.00000100	0.00000033	0.06	0.978
3-way interaction	1	0.00000050	0.00000050	0.00000050	0.09	0.786
Curvature	1	0.00000600	0.00000600	0.00000600	1.06	0.379
Residual error	3	0.00001700	0.00001700	0.00000567		
Pure error	3	0.00001700	0.00001700	0.00000567		
Total	11	0.00003300				

DF, degrees of freedom; Adj SS, adjusted sums of squares; Adj MS, adjusted mean squares; Seq SS, sequential sums of squares.

Table 5. Analysis of variance (ANOVA) table: straightness.

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*
Main effects	3	0.00000850	0.00000850	0.00000283	3.09	0.189
2-way interaction	3	0.00000100	0.00000100	0.00000033	0.36	0.786
3-way interaction	1	0.00000050	0.00000050	0.00000050	0.55	0.514
Curvature	1	0.00000417	0.00000417	0.00000417	4.55	0.123
Residual error	3	0.00000275	0.00000275	0.00000092		
Pure error	3	0.00000275	0.00000275	0.00000092		
Total	11	0.00001692				

DF, degrees of freedom; Adj SS, adjusted sums of squares; Adj MS, adjusted mean squares; Seq SS, sequential sums of squares.

Table 6. Analysis of variance (ANOVA) table: parallelism.

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*
Main effects	3	0.0000654	0.0000654	0.0000218	1.53	0.368
2-way interaction	3	0.0000554	0.0000554	0.0000185	1.30	0.418
3-way interaction	1	0.0000281	0.0000281	0.0000281	1.97	0.255
Curvature	1	0.0332270	0.0332270	0.0332270	2E+03	0.000
Residual error	3	0.0000427	0.0000427	0.0000142		
Pure error	3	0.0000428	0.0000428	0.0000143		
Total	11	0.0334187				

DF, degrees of freedom; Adj SS, adjusted sums of squares; Adj MS, adjusted mean squares; Seq SS, sequential sums of squares.

Main effect and Interaction Effect on Flatness, Straightness and Parallelism

Ignoring the impacts of all other variables of independence, a "main effect" is the impact of one of the independent factors on a dependent variable. When the value of one variable causes the effect of another, this is known as "interaction effect."

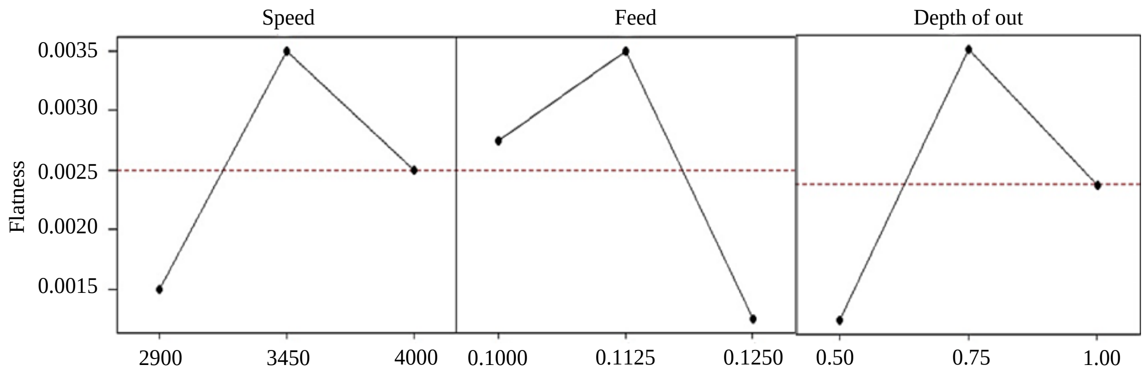

Figure 2. Parametric study on flatness.

Figures 2–4 show the main effect plots of speed, feed, and depth of cut on flatness, straightness, and parallelism, respectively. Figures 5–7 show the interaction effect plots for flatness, straightness, and parallelism, respectively.

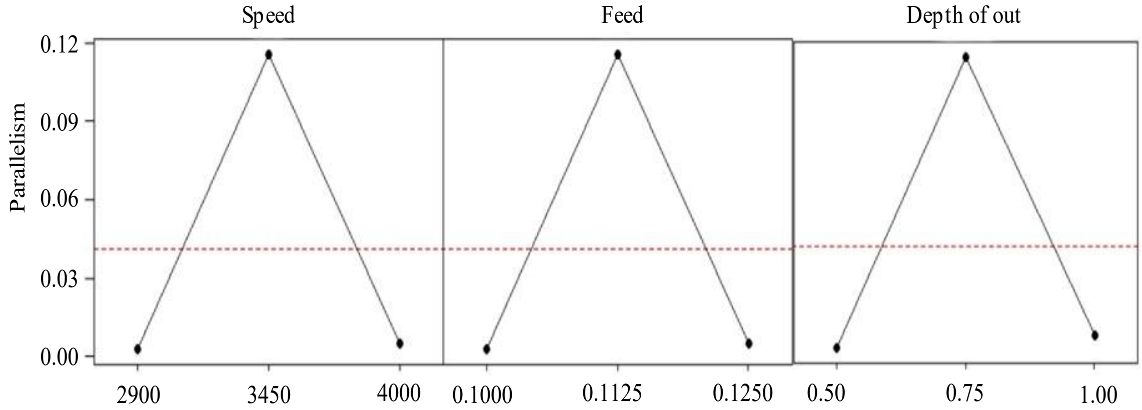

Figure 3. Parametric study on straightness.

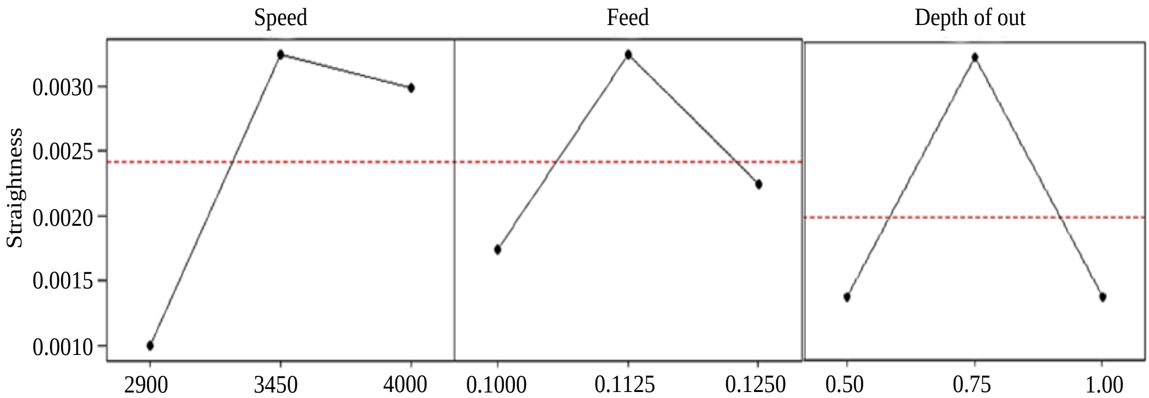

Figure 4. Parametric study on parallelism.

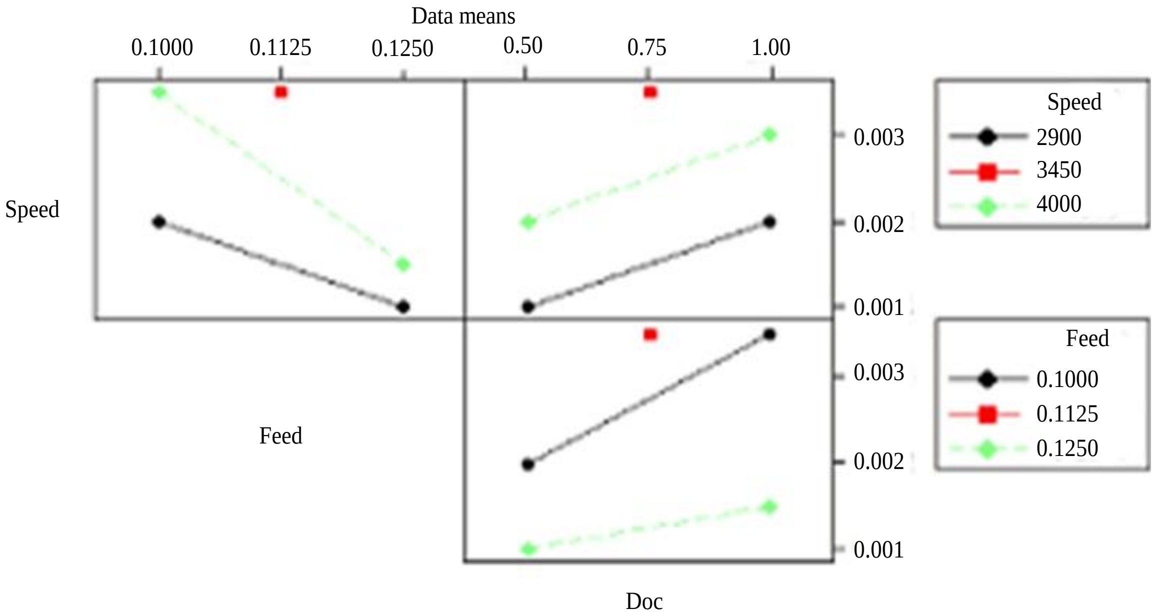

Figure 5. Interaction effect plot for flatness.

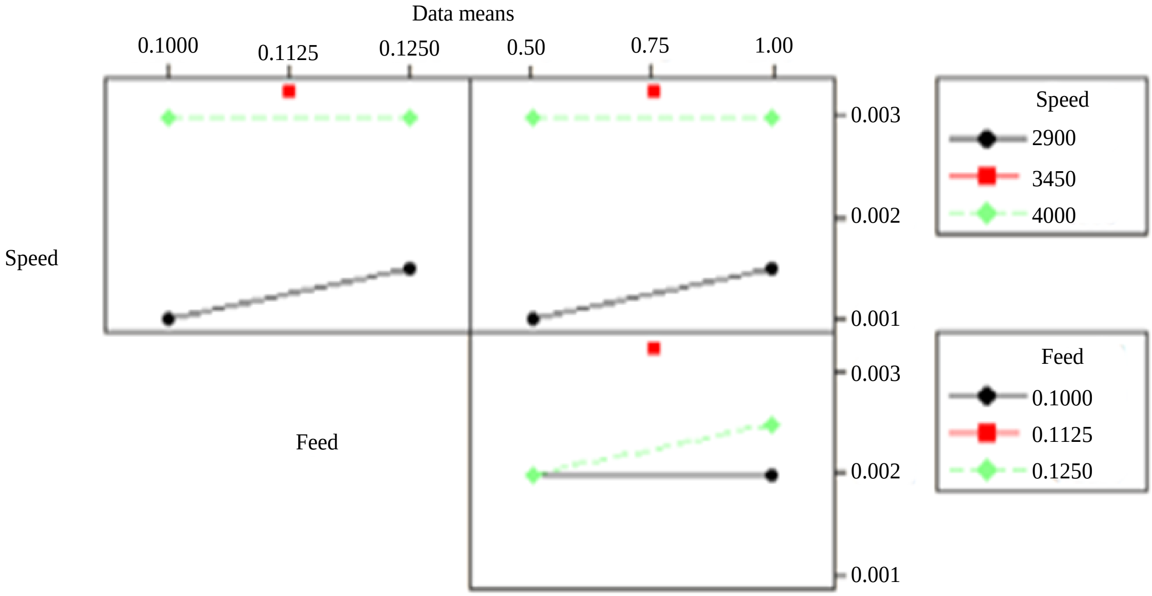

Figure 6. Interaction effect plot for straightness.

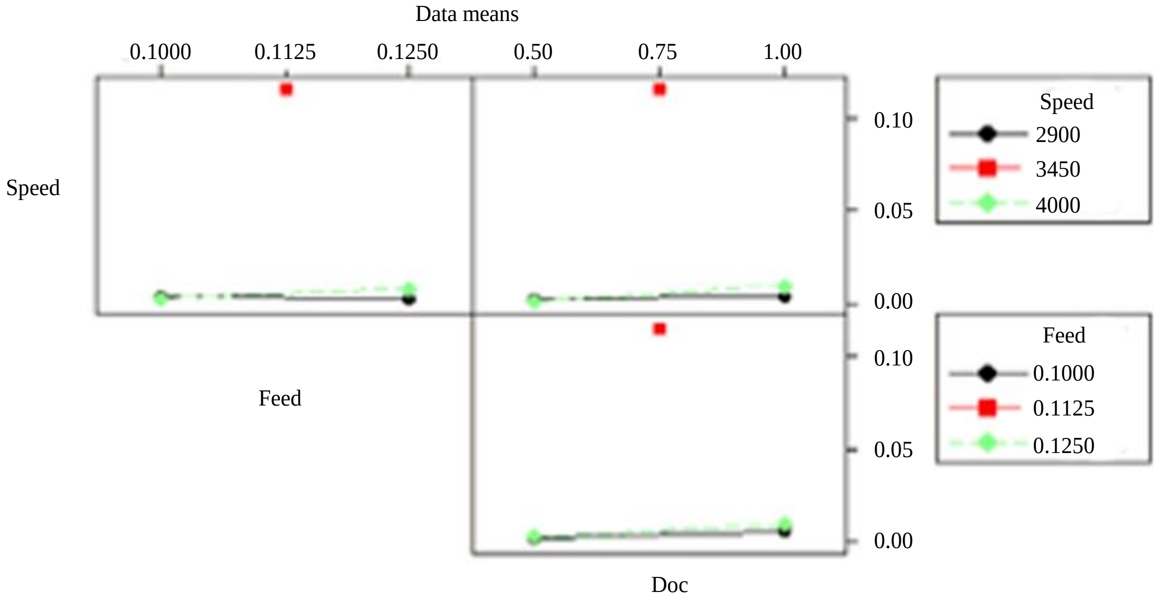

Figure 7. Interaction effect plot for parallelism.

REGRESSION MODEL

An algebraic description of the extrapolation line, the regression model is often used to forecast responses and characterize the relationships between predictor factors and responses. Equations (1), (2), and (3) show the linear regression model for flatness, straightness, and parallelism, respectively [13].

$$y = 0.002 + 0.0005x_1 - 0.00075x_2 + 0.0005x_3 - 0.00025x_1x_2 - 0.00025x_2x_3 + 0.00025x_1x_2x_3 \quad (1)$$

$$y = 0.002 + 0.0001x_1 + 0.00025x_2 - 0.00025x_1x_2 + 0.00025x_2x_3 - 0.00025x_1x_2x_3 \quad (2)$$

$$y = 0.004125 + 0.001125x_1 + 0.001125x_2 + 0.002375x_3 + 0.001625x_1x_2 + 0.001875x_1x_3 + 0.000875x_2x_3 + 0.001875x_1x_2x_3 \quad (3)$$

CONCLUSION

From main effect plots, flatness is minimum at low level of speed and depth of cut, which means that at higher value of feed, flatness is minimum. Flatness minimum at 2900 rpm, 0.1125 mm/rev, and depth of cut 0.5 mm. However, straightness and parallelism are minimum at low levels of all the independent variables. Straightness minimum at 2900 rpm, 0.1 mm/rev, and depth of cut 1.0 mm. Parallelism minimum at 2900 rpm, 0.1 mm/rev, and depth of cut 0.5 mm. The interaction plots for flatness and parallelism indicated that there is no interaction between the independent variables. On the other hand, the straightness interaction plot suggests a little interaction between depth of cut, feed, and speed. Through the models are inadequate, they could be used as a means to understand that the machining parameters are influencing the geometry of the component produced.

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