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# Experimental Investigation of Perpendicularity and Surface Finish of Aluminium T6 6082 Machined on VMC 430

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## Abstract

Aluminium T6 6082 has a good strength-to-weight ratio, lightweight and capable of withstanding enormous load, so it is widely used in automotive, aerospace, and marine industries. The surface roughness and perpendicularity, a Geometric Dimensioning & Tolerancing control (GD&T), play a major role in reducing the rate of rejection between matting parts during their assembly. The machining parameters like spindle speed, feed, and depth of cut have great influence on surface roughness and perpendicularity. It is necessary to investigate the effect of these parameters for Aluminium T6 6082 material. In this study $2^3$ full factorial design with four centre points is utilised to optimise these parameters for face milling and end milling machining process performed on vertical machining centre. The analysis of variance (ANOVA) is used to determine the dominant input parameters (spindle speed, feed, and depth of cut) having significant influence on the output parameters (perpendicularity and surface roughness). It was observed that the depth of cuts is most influential factor, followed by feed and spindle speed for surface roughness and for perpendicularity the feed is most influential factor, followed by depth of cut and spindle speed.

**Keywords**: Spindle speed; Feed; Depth of Cut; Perpendicularity; Surface Roughness; Face Milling; End Milling; GD&T

## 1. Introduction

Milling is a basic machining technique used to create flat contoured surfaces, helical surfaces, thread cutting, gear teeth, and helical grooves using a multi-tooth cutting tool. It is the most common method for shaping metal components and diverse curved surfaces. During this procedure, the cutting tool rotates either parallel to or perpendicular to the feed direction in relation to the machined surface. High quality, in terms of the geometric and dimensional precision of the work piece, is the primary emphasis of today's machining industry as a challenge in aerospace, marine and automotive industrial sectors. The produced product will have accurate dimensions and geometric tolerances for a snug fit and easy assembly.

To control the workpiece's orientation, Geometric Dimensioning and Tolerancing (GD&T) parameters like Perpendicularity are used in this study. GD&T aims to guarantee that components fit together properly and work as intended, while decreasing manufacturing costs and enhancing quality control. With the use of GD&T, there will be effective communication between designers, engineers, and manufacturers, and even if there are variations in manufacturing or assembly, the fit and functionality will be enhanced. GD&T is essential in areas where accuracy and dependability are crucial.

Aluminium T6 6082 is a typical aluminium alloy used in a broad variety of industrial applications. The T6 temper, created by heating the metal at 500°C and quenching in water which strengthens and hardens the alloy and making it appropriate for numerous uses and easy to shape. This alloy is renowned for its superior strength, tensile strength, and corrosion resistance. Its high strength-to-weight ratio makes it light and strong, due to its high tensile, yield, and fatigue strengths making it suitable for applications requiring high strength and durability. Aluminium T6 6082 has a number of advantageous properties that make it an excellent material for a wide range of applications. It is used a lot in the automotive, aerospace, and maritime industries, in construction industry to make building facades, windows, doors, and roofing systems, used to make trucks, trailers, and buses, as well as other parts for transportation, used to make golf clubs, tennis racquets, and bicycle frames, and used for more than just making tools, machinery, and electrical equipment. Casting, extruding, forging, and rolling are just some of the methods that can be used to manufacture aluminium T6 6082.

## 2. Literature Review

The researcher investigated how several parameters affect surface roughness during aluminium alloy milling. Analysing surface roughness using analysis of variance, researchers considered spindle speed and feed rate to assessed the surface roughness using ANOVA [1]. A milling machine and carbide tools with two cutting blades were used to examine the surface roughness of 7075-T6 aluminium. Feed ratio and speed rate enhance surface roughness during milling, although depth of cut does not [2]. This research uses artificial neural network and genetic algorithm to determine cutting parameters for least surface roughness. Lower machining tolerance increases surface roughness [3]. Research investigates the impacts of spindle speed, cutting feed rate, and depth of cut on surface roughness and design a multiple regression model. cutting feed is dominant factor The most important interactions, that effect surface roughness of machined surfaces, were between the cutting feed and depth of cut, and between cutting feed and spindle speed [4]. Responsive Ant Colony Optimization optimises surface roughness in milling Molded Aluminium alloys (AA6061-T6) using (RACO). RSM and ACO are employed. This analysis identified the best parameters and most important elements (cutting speed, federate, axial depth and radial depth). Feedrate affects surface roughness most, according to the first order model [5][6]. Three-dimensional surface plots analyse carbide end milling aluminium alloy cutting parameters. ANNs determine surface roughness-cutting parameter connection (i.e., spindle speed, feed, and depth of cut). MATLAB ANN propagates feedforward backward. 3-12-1 network predicted surface roughness best. Unseen data enhanced network surface roughness prediction. Component surface finish cutting parameters are offered. Calculated cutting parameters enhance surface quality and tool life [7][8][9].

Surface roughness is simulated and improved for dry and wet end milling 6061 aluminium alloy using HSS and carbide tools. Experimental data and cutting settings effect surface roughness. Experimental data provide second-order mathematical models of different machining parameters. GA and regression equation set bottom surface roughness cutting parameters, Spindle speed and feed rate effect surface roughness more than cut depth [10]. This research optimises surface roughness while milling with carbide-inserted on AA6061-T6 aluminium alloys. Design of experiments and response surface approach are used. Axial depth, cutting speed, and radial depth affect surface roughness less than feed rate. Low cutting speed, axial depth, and high feed rate promote surface roughness. Grey relational analysis was used to optimise multi-responses by modifying weights depending on process quality or productivity [11][12]. Ball-nose end mills were used to evaluate LM6 Al alloy surface quality. Experimental design and mathematical modelling employed the Response Surface Methodology Box Behnken approach. Analysis of Variance gave the model an R-squared value of 92.42 percent. Cutting speed and feed rate influenced most. Surface roughness optimised machining settings (cutting speed, feed rate, and depth of cut). Genetic algorithm is used to calculate minimum surface roughness. Cutting speed and feed rate more significant than depth of cut [12-14]. This study examined how cutting parameters affect surface roughness during end milling aluminium 6061 under minimum quantity lubrication (MQL) conditions. The surface quality of machining parameters was tested and least square mathematical models were developed. Spindle speed (N), feed rate (f), axial depth of cut (a), and radial depth of cut (r) predict surface roughness. Spindle speed impacts surface roughness more than feed rate. Surface roughness is unaffected by radial and axial depth of cut [15][16]. This research studied how spindle speed, feed, and depth of cut impact surface roughness and flatness during face milling of Wrought Cast Steel, a geometric dimensioning and tolerancing. $2^3$ full factorials is used to find optimal process parameters using DOE. Surf test SV2100 evaluates surface roughness using a rectangular grid extraction, whereas coordinate measurement equipment assesses flatness (CMM). ANOVA and main effect and interaction plots for input and output parameters indicate important variables. Second-order regression follows. Comparing the experimental result to the regression model shows a maximum flatness error of 7.06 percent and a surface roughness error of 10.98 percent [17]. This research provides the latest experimental data on cutting force and surface roughness as process response parameters. $3^4$ factorial experiments of AL 2024-T351 aluminium alloy end-milling using conservative cutting settings. ANOVA and regression analysis were used to examine how process parameters affect low cutting force and surface roughness. Cutting force affected surface roughness [18].

This research examined cutting force, moment, and surface roughness while end milling aluminium 6082-T6 using a solid carbide end mill at different revolutions, feed rates, and depths of cut. Feed rate affects aluminium 6082-T6 end milling surface roughness. Feed rate increases surface roughness, whereas spindle speed and depth of cut decrease it [19]. Researchers explored how drilling cutting parameters affect hole roundness and straightness. This study examines a VMC's drilled hole tolerance. Researchers examined factors like circularity, cylindricity, perpendicularity, etc. is most effect on work piece geometry. DOE and regression models have predicted how process parameter changes impact work piece form. This study examines drilling response parameters cylindricity and perpendicularity [20]. This research reveals Grey relational analysis was used to anticipate, optimise, and investigate

WCB material drilling cylindricity and perpendicularity. They evaluated how spindle speed, feed, and depth of cut affected response characteristics such cylindricity and perpendicularity, a form of geometric dimensioning & tolerancing, during drilling of Wrought Cast Steel Grade B (WCB) material with SOMX 050204 DT insert. Design of experiments (DOE) with $3^3$ full factorials and two replicates is used to find the best process parameters. CMM determines circularity and perpendicularity (coordinate measuring machine). ANOVA is used to discover key variables, and main effect and interaction graphs are presented for input and output parameters [21]. The researcher used magnesium AZ31 for drilling. Controlling circularity, perpendicularity, and cylindricity reduces compressive and shear stress, extending fastener life. Deviations increase compression, shear, fatigue, and assembly time. Empirical model and Desirability Function Method were used to optimise process planning engineer use (DFA). Reduce reactions with GRA. DFA and GRA comparison shows GRA's circularity and cylindricity advantages [22].

From the foregoing analysis of the literature, it was determined that no more research was conducted on aluminium T6 6082. This study aims to determine, using a $2^3$ full factorial design, the major factors (speed, feed, and depth of cut) that influence the surface roughness and perpendicularity of aluminium T6 6082 material when machined on a vertical milling machine (VMC) with a face mill tool for face milling operation and an end mill tool for end milling operation.

## 3. Experimentation

3.1. Work piece material, Machine tool and cutting tool

The work piece material is Aluminium T6 6082. Its chemical composition is shown in table 1 and table 2 shows the physical properties. Experiments were carried out on the Jyoti 430 Milling spindle motor power of 7 Kw. 90 mm diameter face mill tool made from HSS (High Speed Steel) and 12 mm diameter end mill tool made from HSS (High Speed Steel) has been used for this investigation.

*Table 1 Chemical Properties of Aluminium T6 6082*

| Element | Weight Percentage (%) |
|---|---|
| **Aluminium** | 95.2 to 98.3 |
| **Chromium** | 0.25 % max. |
| **Copper** | 0.1 % max. |
| **Iron** | 0.5 % max |
| **Magnesium** | 0.6 to 1.2% |
| **Manganese** | 0.4 to 1.0 % |
| **Silicon** | 0.7 to 1.3% |
| **Titanium** | 0.1 % max |
| **Zinc** | 0.2 % max |
| **residuals** | 0.15 % max |

*Table 2 Physical Properties of Aluminium T6 6082*

| Properties | Value |
|---|---|
| **Density** | 2.71 gm/cc |
| **Youngs Modulus** | 71 GPa |
| **Ultimate Tensile Strength** | 140 to 330 MPa |
| **Yield Strength** | 260 MPa |
| **Thermal Expansion** | 23.1 µm/m-K |

3.2. Experimental Procedure

Experiments are carried out on blocks having size of 50 mm x 50mm x 25 mm of Aluminium T6 6082 material. Spindle speed, Feed, and Depth of Cut are chosen as experimental input variables in accordance with a $2^3$ full factorial with four centre points experimental design [23]. The tests are performed with a 90 mm face mill tool for face milling operation and a 12 mm end mill tool for end milling operation. First, the machining is performed on all six sides of the block and then after face milling process is carried out on top face of block and end milling is carried out on the side face of the block, the number of passes and coolant flow rate are kept constant. The level of the input variables for face milling is shown in the table 3 and table 4 shows level of input variables for end milling [24]. Block is clamped by using vice. Figure 1 shows the face milling operation and figure 2 shows the end milling operation.

*Table 3 Factors and Levels for Face Milling*

| Factors | Coded factors | Low level (-) | High level (+) | Centre points |
|---|---|---|---|---|
| Spindle speed (rpm) | A | 1700 | 1900 | 1800 |
| Feed (mm/min.) | B | 3064 | 5712 | 4322 |
| Depth of cut (mm) | C | 0.5 | 1 | 0.75 |

*Table 4 Factors and Levels for End Milling*

| Factors | Coded factors | Low level (-) | High level (+) | Centre points |
|---|---|---|---|---|
| Spindle speed (rpm) | A | 2000 | 3000 | 2500 |
| Feed (mm/min.) | B | 880 | 1560 | 1200 |
| Depth of cut (mm) | C | 0.3 | 0.5 | 0.4 |

*Table 5 Factorial Design for Face Milling*

| Combinations | Runs | A | B | C | Speed | Feed | Depth of Cut |
|---|---|---|---|---|---|---|---|
| 1 | 1 | - | - | - | 1700 | 3064 | 0.5 |
| 2 | a | + | - | - | 1900 | 3064 | 0.5 |
| 3 | b | - | + | - | 1700 | 5712 | 0.5 |
| 4 | ab | + | + | - | 1900 | 5712 | 0.5 |
| 5 | c | - | - | + | 1700 | 3064 | 0.75 |
| 6 | ac | + | - | + | 1900 | 3064 | 0.75 |
| 7 | bc | - | + | + | 1700 | 5712 | 0.75 |
| 8 | abc | + | + | + | 1900 | 5712 | 0.75 |
| 9 | centre points | 0 | 0 | 0 | 1800 | 4322 | 1 |
| 10 | | 0 | 0 | 0 | 1800 | 4322 | 1 |
| 11 | | 0 | 0 | 0 | 1800 | 4322 | 1 |
| 12 | | 0 | 0 | 0 | 1800 | 4322 | 1 |

*Table 6 Factorial Design for End Milling*

| Combinations | Runs | A | B | C | Speed | Feed | Depth of Cut |
|---|---|---|---|---|---|---|---|
| 1 | 1 | - | - | - | 2000 | 880 | 0.3 |
| 2 | a | + | - | - | 3000 | 880 | 0.3 |
| 3 | b | - | + | - | 2000 | 1560 | 0.3 |
| 4 | ab | + | + | - | 3000 | 1560 | 0.3 |
| 5 | c | - | - | + | 2000 | 880 | 0.5 |
| 6 | ac | + | - | + | 3000 | 880 | 0.5 |
| 7 | bc | - | + | + | 2000 | 1560 | 0.5 |
| 8 | abc | + | + | + | 3000 | 1560 | 0.5 |
| 9 | centre points | 0 | 0 | 0 | 2500 | 1200 | 0.4 |
| 10 | | 0 | 0 | 0 | 2500 | 1200 | 0.4 |
| 11 | | 0 | 0 | 0 | 2500 | 1200 | 0.4 |
| 12 | | 0 | 0 | 0 | 2500 | 1200 | 0.4 |

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*Figure 1 Face Milling Operation*


3.3. Measuring Techniques

A Mitutoyo portable surface roughness tester is used to assess the surface's roughness as shown in figure 3, Hexagon CMM (coordinate measuring machine) is used to check the Perpendicularity as shown in figure 4. Figure 5 shows a sample reading of perpendicularity measured through coordinate measuring machine.


*Figure 4 Surface Roughness Measurement*

*Figure 3 Perpendicularity measurement on CMM*

| ⊥ | MM | PERP1 - PLN4 TO PLN2 | | | | | |
|---|---|---|---|---|---|---|---|
| AX | NOMINAL | MEAS | +TOL | -TOL | DEV | OUTTOL | |
| M | 0 | 0.018 | 0.0100 | 0 | 0.018 | 0.008 | |

*Figure 5 Sample reading of Perpendicularity from CMM*

## 4. Result, and Analysis

ANOVA is used to determine the significant factors, each factor's influence on the response, and the percentage contribution of each factor. Table 7 demonstrates the responses based on coded variables and treatment combinations using $2^3$ full factorial with four centre point experimental design for surface roughness and perpendicularity measured through CMM machine and surface roughness tester.

*Table 7 Result of surface roughness and perpendicularity for various treatment combinations*

| Treatment combination | Coded factors | | | Responses | |
|---|---|---|---|---|---|
| | A | B | C | Perpendicularity (mm) | Surface roughness (μm) |
| **1** | - | - | - | 0.018 | 1.56 |
| **a** | + | - | - | 0.041 | 2.21 |
| **b** | - | + | - | 0.057 | 2.73 |
| **ab** | + | + | - | 0.027 | 1.98 |
| **c** | - | - | + | 0.037 | 1.46 |
| **ac** | + | - | + | 0.028 | 1.42 |
| **bc** | - | + | + | 0.043 | 2.49 |
| **abc** | + | + | + | 0.032 | 1.24 |
| **centre points** | 0 | 0 | 0 | 0.035 | 1.78 |
| | 0 | 0 | 0 | 0.043 | 1.87 |
| | 0 | 0 | 0 | 0.045 | 1.88 |
| | 0 | 0 | 0 | 0.037 | 1.73 |

4.1. ANOVA for Surface Roughness

Table 8 shows the ANOVA result of surface roughness.

*Table 8 ANOVA table for Surface Roughness*

| Source | DF | Seq SS | Adj SS | Adj MS | F-Value | P-Value | Contribution |
|---|---|---|---|---|---|---|---|
| Model | 8 | 2.12672 | 2.12672 | 0.265841 | 50.8 | 0.004 | 99.27% |
| Linear | 3 | 1.07914 | 1.07914 | 0.359712 | 68.73 | 0.003 | 50.37% |
| A | 1 | 0.24151 | 0.24151 | 0.241512 | 46.15 | 0.007 | 11.27% |
| B | 1 | 0.40051 | 0.40051 | 0.400512 | 76.53 | 0.003 | 18.69% |
| C | 1 | 0.43711 | 0.43711 | 0.437112 | 83.52 | 0.003 | 20.40% |
| 2-Way Interactions | 3 | 1.02954 | 1.02954 | 0.343179 | 65.58 | 0.003 | 48.05% |
| A*B | 1 | 0.85151 | 0.85151 | 0.851513 | 162.71 | 0.001 | 39.75% |
| A*C | 1 | 0.17701 | 0.17701 | 0.177013 | 33.82 | 0.01 | 8.26% |
| B*C | 1 | 0.00101 | 0.00101 | 0.001012 | 0.19 | 0.69 | 0.05% |
| 3-Way Interactions | 1 | 0.00451 | 0.00451 | 0.004512 | 0.86 | 0.422 | 0.21% |
| A*B*C | 1 | 0.00451 | 0.00451 | 0.004512 | 0.86 | 0.422 | 0.21% |
| Curvature | 1 | 0.01354 | 0.01354 | 0.013537 | 2.59 | 0.206 | 0.63% |
| Error | 3 | 0.0157 | 0.0157 | 0.005233 | | | 0.73% |
| Total | 11 | 2.14242 | | | | | 100.00% |

Table 8 demonstrates that Surface Roughness is found to be significant, form this it is clearly understood that depth of cut is the most significant parameter followed by feed and spindle speed.

4.2. Main Effects plots and Interaction plot

Figure 6 shows, main effect plot of spindle speed, feed and depth of cut vs. surface roughness. From this it can be concluded that surface roughness is minimum at higher level of spindle speed, lower level of feed and higher level of depth of cut. Figure 7 shows, Interaction plot of spindle speed, feed and depth of cut vs. surface roughness. There is a significant amount of interaction between spindle speed and feed, spindle speed and depth of cut. There is no interaction between feed and depth of cut for surface.

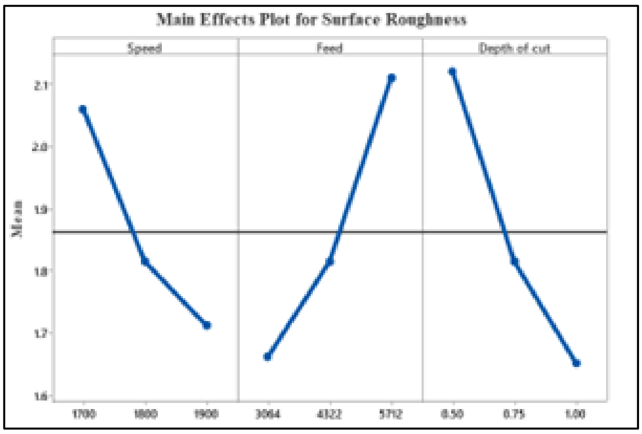


*Figure 7 Main Effect plot of Spindle speed, Feed and Depth of cut vs. Surface Roughness*

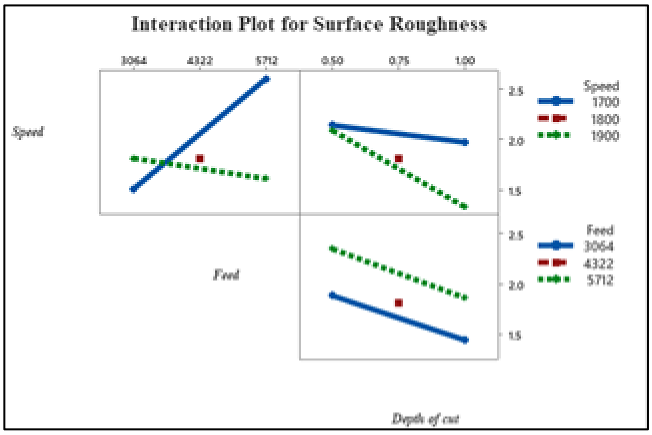


*Figure 6 Interaction plot of Spindle speed, Feed and Depth of cut vs. Surface Roughness*

4.3. ANOVA for Perpendicularity

Table 7 shows the ANOVA result of perpendicularity

*Table 9 ANOVA table for Perpendicularity*

| Source | DF | Seq SS | Adj SS | Adj MS | F-Value | P-Value | Contribution |
|---|---|---|---|---|---|---|---|
| Model | 8 | 0.001055 | 93.94% | 0.001055 | 0.000132 | 5.82 | 93.94% |
| Linear | 3 | 0.000245 | 21.85% | 0.000245 | 0.000082 | 3.61 | 21.85% |
| A | 1 | 0.000091 | 8.12% | 0.000091 | 0.000091 | 4.02 | 8.12% |
| B | 1 | 0.000153 | 13.64% | 0.000153 | 0.000153 | 6.76 | 13.64% |
| C | 1 | 0.000001 | 0.10% | 0.000001 | 0.000001 | 0.05 | 0.10% |
| 2-Way Interactions | 3 | 0.000427 | 38.06% | 0.000427 | 0.000142 | 6.28 | 38.06% |
| A*B | 1 | 0.000378 | 33.67% | 0.000378 | 0.000378 | 16.68 | 33.67% |
| A*C | 1 | 0.000021 | 1.88% | 0.000021 | 0.000021 | 0.93 | 1.88% |
| B*C | 1 | 0.000028 | 2.50% | 0.000028 | 0.000028 | 1.24 | 2.50% |
| 3-Way Interactions | 1 | 0.000325 | 28.95% | 0.000325 | 0.000325 | 14.34 | 28.95% |
| A*B*C | 1 | 0.000325 | 28.95% | 0.000325 | 0.000325 | 14.34 | 28.95% |
| Curvature | 1 | 0.000057 | 5.08% | 0.000057 | 0.000057 | 2.52 | 5.08% |
| Error | 3 | 0.000068 | 6.06% | 0.000068 | 0.000023 | | 6.06% |
| Total | 11 | 0.001123 | 100.00% | | | | 100.00% |

Table 7 demonstrates that Perpendicularity is found to be insignificant.

Through ANOVA it is observed that surface roughness is significant since the p-value is smaller than 0.05, indicating that a confidence level of 95% has been attained. It can be shown that depth of cuts is the most influential factor, followed by feed and spindle speed. On the other hand, perpendicularity is deemed insignificant since the 95% confidence level is not met. To make the perpendicularity significant, a second set of trials were undertaken using the same tool and machine, but with different feed, and number of steps in z direction during end milling.

4.4. Factors and Levels for End Milling

The factor and level of spindle speed, feed, and depth of cut for end milling operations are shown in Table 10. The factorial design of the experimental trials is shown in Table 11.

*Table 10 Factors and Levels for End Milling*

| Factors | Coded factors | Low level (-) | High level (+) | Centre points |
|---|---|---|---|---|
| Spindle speed (rpm) | A | 2000 | 3000 | 2500 |
| Feed (mm/min.) | B | 88 | 156 | 120 |
| Depth of cut (mm) | C | 0.3 | 0.5 | 0.4 |

*Table 11 Factorial Design for End Milling*

| Combinations | Runs | A | B | C | Speed | Feed | Depth of Cut |
|---|---|---|---|---|---|---|---|
| 1 | 1 | - | - | - | 2000 | 88 | 0.3 |
| 2 | a | + | - | - | 3000 | 88 | 0.3 |
| 3 | b | - | + | - | 2000 | 156 | 0.3 |
| 4 | ab | + | + | - | 3000 | 156 | 0.3 |
| 5 | c | - | - | + | 2000 | 88 | 0.5 |
| 6 | ac | + | - | + | 3000 | 88 | 0.5 |
| 7 | bc | - | + | + | 2000 | 156 | 0.5 |
| 8 | abc | + | + | + | 3000 | 156 | 0.5 |
| 9 | centre points | 0 | 0 | 0 | 2500 | 120 | 0.4 |
| 10 | | 0 | 0 | 0 | 2500 | 120 | 0.4 |
| 11 | | 0 | 0 | 0 | 2500 | 120 | 0.4 |
| 12 | | 0 | 0 | 0 | 2500 | 120 | 0.4 |

4.5. Results for Perpendicularity

Table 12 demonstrates the responses based on coded variables and treatment combinations using $2^3$ full factorial with four centre point experimental design for perpendicularity measured through CMM machine and surface roughness tester.

*Table 12 Result of perpendicularity for various treatment combinations*

| Treatment combination | Coded factors | | | Responses |
|---|---|---|---|---|
| | A | B | C | Perpendicularity (mm) |
| **1** | - | - | - | 0.029 |
| **a** | + | - | - | 0.03 |
| **b** | - | + | - | 0.025 |
| **ab** | + | + | - | 0.013 |
| **c** | - | - | + | 0.024 |
| **ac** | + | - | + | 0.026 |
| **bc** | - | + | + | 0.071 |
| **abc** | + | + | + | 0.087 |
| **centre points** | 0 | 0 | 0 | 0.027 |

| | | | | |
|---|---|---|---|---|
| | 0 | 0 | 0 | 0.02 |
| | 0 | 0 | 0 | 0.024 |
| | 0 | 0 | 0 | 0.025 |

4.6. ANOVA for Perpendicularity

Table 13 shows the ANOVA result of perpendicularity.

*Table 13 ANOVA table for Perpendicularity*

| Source | DF | Seq SS | Adj SS | Adj MS | F-Value | P-Value | Contribution |
|---|---|---|---|---|---|---|---|
| Model | 8 | 0.005301 | 0.005301 | 0.000663 | 76.46 | 0.002 | 99.51% |
| Linear | 3 | 0.002492 | 0.002492 | 0.000831 | 95.86 | 0.002 | 46.79% |
| A | 1 | 0.000006 | 0.000006 | 0.000006 | 0.71 | 0.462 | 0.11% |
| B | 1 | 0.000946 | 0.000946 | 0.000946 | 109.17 | 0.002 | 17.76% |
| C | 1 | 0.00154 | 0.00154 | 0.00154 | 177.71 | 0.001 | 28.91% |
| 2-Way Interactions | 3 | 0.002185 | 0.002185 | 0.000728 | 84.05 | 0.002 | 41.03% |
| A*B | 1 | 0 | 0 | 0 | 0.01 | 0.912 | 0.00% |
| A*C | 1 | 0.000105 | 0.000105 | 0.000105 | 12.13 | 0.04 | 1.97% |
| B*C | 1 | 0.00208 | 0.00208 | 0.00208 | 240.01 | 0.001 | 39.05% |
| 3-Way Interactions | 1 | 0.000091 | 0.000091 | 0.000091 | 10.51 | 0.048 | 1.71% |
| A*B*C | 1 | 0.000091 | 0.000091 | 0.000091 | 10.51 | 0.048 | 1.71% |
| Curvature | 1 | 0.000532 | 0.000532 | 0.000532 | 61.39 | 0.004 | 9.99% |
| Error | 3 | 0.000026 | 0.000026 | 0.000009 | | | 0.49% |
| Total | 11 | 0.005327 | | | | | 100.00% |

Table 13 demonstrates that Perpendicularity is found to be significant, form this it is clearly understood that depth of cut is the most significant parameter while spindle speed has very less contribution.

4.7. Main Effects plots and Interaction plot

Figure 8 shows, main effect plot of spindle speed, feed and depth of cut vs. perpendicularity. From this it can be concluded that the deviation in perpendicularity is minimum at the centre level of each input parameter. Figure 9 shows, Interaction plot of spindle speed, feed and depth of cut vs. perpendicularity. There is a significant amount of interaction between feed and depth of cut, spindle speed and depth of cut. There is no interaction between spindle speed and feed for perpendicularity as response.

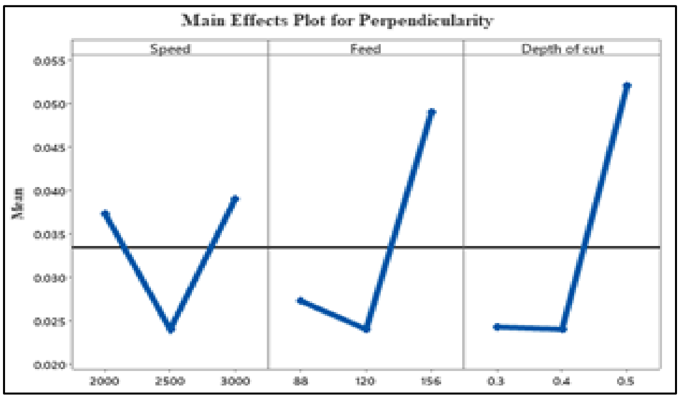


*Figure 8 Main Effect plot of Spindle speed, Feed and Depth of cut vs. Perpendicularity*

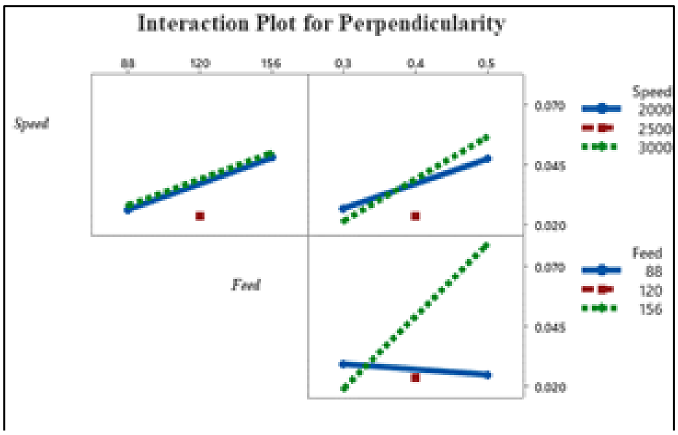


*Figure 9 Interaction plot of Spindle speed, Feed and Depth of cut vs. Perpendicularity*

## 5. Conclusion & Future Scope

In the eighth combination of the experiment, the lowest surface roughness, 1.24 Ra was achieved at 1900 rpm spindle speed 5712 mm/min feed and 1mm depth of cut. It was observed that depth of cuts is the most influential factor, followed by feed and spindle speed for surface roughness. The perpendicularity was deemed insignificant owing to the increased feed, which reduces the tool's travel time on the workpiece surface and increases the thrust force on the end mill tool. To make the perpendicularity significant, the number of end milling machining cycles were raised from 5 to 10, and the depth in the z axis was decreased from 5 mm to 2.5 mm, feed was also reduced; this improved the perpendicularity and made it significant. The minimal deviation in perpendicularity, 0.013 mm was attained on the fourth combination at 3000 rpm spindle speed 156 mm/min feed and 0.3 mm depth of cut. It was observed that feed is the most influential factor, followed by depth of and spindle speed for perpendicularity. Moreover, this model can further be optimised through the use of multi-variable optimisation - Grey Relational Analysis.

## 6. Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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