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## Impact of spindle tilt and machining parameters on surface roughness in milling

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### Abstract

This study aims to analyze the influence of spindle tilt and machining parameters (feed rate, depth of cut, and spindle speed) on surface roughness in milling operations using a Knuth UFM 2 universal milling machine. A parametric experimental approach was used, where parameters were varied systematically to assess their influence on surface quality. Results show that increasing spindle tilt, feed rate, and depth of cut generally raises surface roughness, while higher spindle speeds reduce it, producing smoother surfaces. The optimal surface quality was achieved during the first up-milling test with a spindle inclination of 30°, feed rate of 108 m/min, spindle speed of 720 rpm, and depth of cut of 0.50 mm, yielding a surface roughness (Ra) of 0.258  $\mu\text{m}$ . In contrast, higher tilt angles and cutting loads significantly degraded surface finish, with roughness increasing by up to 95.91% when spindle tilt was raised from 30° to 60°, by 52.86% when depth of cut increased from 0.50 mm to 1.50 mm, and by 79.25% when feed rate rose from 45 m/min to 233 m/min. Conversely, increasing spindle speed from 148 rpm to 720 rpm reduced Ra by 99.81%. These findings highlight the importance of selecting appropriate parameter combinations to achieve precision, efficiency, and sustainability in milling. The results also provide practical reference for industrial applications and vocational training in manufacturing engineering.

### Keywords:

Milling machine, surface roughness, spindle tilt, depth of cut, feed rate, spindle speed.

### 1 Introduction

Machining processes are a vital part of the manufacturing industry due to their ability to produce components with high precision and excellent surface quality [1]. Among the various machining methods available, milling is one of the most widely used techniques, both in industrial sectors and vocational education [2]. This popularity is attributed to its flexibility in shaping various geometries, including flat surfaces and complex contours, as well as its capability to produce relatively smooth surface finishes [3][4]. One of the most critical aspects of milling is the surface quality of the machined workpiece, which is commonly evaluated based on surface roughness parameters [5][6]. Surface roughness plays a significant role in determining the mechanical functionality of components, such as wear resistance, frictional behavior, fatigue life, assembly fit, and the quality of contact between surfaces [7][8]. Therefore, controlling surface roughness is one of the primary objectives in precision machining practices.

Several factors are known to influence surface roughness in milling processes, including spindle speed, feed rate, and depth of cut [9][10]. These three parameters significantly affect the behavior

of the cutting zone, including the forces involved, temperature, chip formation, and the level of vibration during machining. Variations in the settings of these parameters can result in markedly different surface finishes, even when using the same cutting tool and workpiece material [11][12]. In addition to these primary parameters, another relevant factor that warrants further investigation is spindle tilt. Spindle tilt refers to the angular deviation of the spindle axis relative to the flat surface of the workpiece, typically caused by manual adjustment of the machine head [13] [14]. Changes in this angle can influence the cutting orientation, the direction of cutting forces, and the contact area distribution between the tool and the workpiece. Such variations in orientation can significantly impact surface formation and the resulting surface roughness values [15][16].

In practice, conventional milling machines are still widely used in various industrial settings, particularly in small and medium-sized enterprises as well as technical education institutions. One commonly used type is the Knuth UFM 2 universal milling machine, which is designed to support flexibility in manually adjusting machining parameters and spindle angles [2]. This machine allows operators to perform a wide range of cutting configurations, making it well-suited for both experimental simulations in educational environments and practical applications in workshops and small to medium-scale production units [1].

The use of conventional machines such as the Knuth UFM 2 is essential to investigate, as empirical data and scientific references regarding the performance of this type of machine remain limited in the existing literature. In practice, however, these machines continue to dominate usage in many technical workshops and traditional production units that have not fully transitioned to automation or numerical control systems [17][18]. Therefore, research on the influence of machining parameters, including spindle tilt on conventional milling machines, is both highly relevant and urgently needed to address real-world technical demands [19]. Although the effects of parameters such as spindle speed, feed rate, and depth of cut on surface roughness have been widely studied, research that simultaneously examines these factors in combination with spindle tilt, particularly on universal milling machines, remains scarce [20] [21].

Nevertheless, some authors have investigated the effects of spindle tilt and machining parameters on milling machine vibrations, which influence the stability of the machining process [1][2]. However, studies that simultaneously examine surface quality along with variations in spindle tilt, workpiece tilt and machining parameters remain scarce. This highlights a research gap that needs to be addressed in order to improve our understanding of the interactions among machining parameters. Such a comprehensive understanding is crucial for informed technical decision-making, both in conventional industrial environments and in vocational education settings where manual machining systems are still in use.

Based on the aforementioned background, this study aims to systematically analyze the influence of spindle tilt and machining parameters, including spindle speed, feed rate, and depth of cut, on surface roughness in milling operations using the Knuth UFM 2 universal milling machine. The research was conducted through an experimental approach with a controlled variable design to evaluate both the direct effects and the interactions among parameters on the surface quality of the machined workpiece [22][23]. This study is expected to provide both scientific and practical contributions. Scientifically, it aims to enrich the body of knowledge on machining characteristics using conventional milling machines. Practically, the findings can serve as a technical reference for machine operators, training instructors, and industry practitioners in determining optimal parameter combinations to achieve high-quality surface finishes with efficient machining performance, particularly in industrial settings that still rely on conventional machining technologies [24].

## 2 Research methods

### 2.1 Type and research design

This study was conducted using a laboratory experimental approach aimed at analyzing the influence of spindle tilt and various machining parameters on surface roughness (Ra) in milling operations. The method applied in this research is a single-parameter variation approach, in which one independent variable is varied in each testing cycle while the other variables are kept constant. This approach is intended to provide a more specific and measurable understanding of the direct effect of each parameter on the surface quality of the machined workpiece.

Although this study employs a single-parameter variation approach to isolate the effects of individual parameters, this method has limitations in capturing simultaneous interaction effects among multiple parameters, such as between feed rate and depth of cut or other relevant factors. Therefore, further studies using a factorial design will be conducted to comprehensively analyze multi-parameter interaction effects.

### 2.2 Equipment and materials

The experiment was conducted in a machining laboratory using carefully selected equipment and materials to ensure the accuracy and consistency of test results. All components used were specifically adapted to meet the objectives of the study, particularly in analyzing the effects of spindle tilt and machining parameters on surface roughness in milling operations. The equipment and materials used in this research are:

#### 2.2.1 Milling machine

The milling machine used in this study was the Knuth UFM 2 universal milling machine, which allows for manual adjustment of spindle tilt. This machine was selected for its flexibility in enabling variations in cutting angles required for the experiments (Fig. 1).



Fig. 1. Knuth UFM 2 universal milling machine.

#### 2.2.2 Cutter

The cutter used in this study was a 16 mm diameter 4-flute High Speed Steel (HSS) end mill. This type of tool was selected for its capability to perform precise cutting on low-carbon steel (Fig. 2).



Fig. 2. HSS end mill cutter with 16 mm diameter.

#### 2.2.3 Workpiece

The workpiece material used was low-carbon steel (mild steel) with dimensions of 100 mm in length, 65 mm in width, and 15 mm in thickness. All workpieces were prepared with uniform initial surface conditions to ensure consistency in the measurement results (Fig. 3).

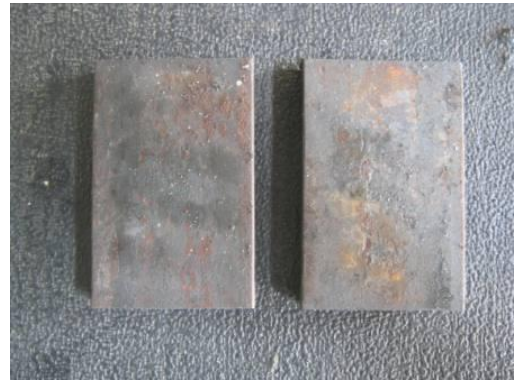


Fig. 3. Workpiece.

#### 2.2.4 Surface roughness measuring instrument

Surface roughness was measured using a Mitutoyo SJ-310 Surface Roughness Tester, which offers high precision and complies with ISO 4287 measurement standards. Measurements were taken at two different points on each workpiece surface (Fig. 4).



Fig. 4. Mitutoyo SJ-130 surface roughness tester.

In addition, supporting equipment such as a machine vice, clamping tools, and various safety gears, including safety goggles and gloves, were used to ensure operator safety during the experiment. All testing was conducted under controlled laboratory conditions to minimize external disturbances that could affect the observations. All equipment and materials were in good working condition and were calibrated beforehand according to laboratory standards to ensure the validity of the experimental results.

### 2.3 Research variables

In this study, the variables are classified into three categories: independent variables, dependent variables, and controlled variables.

#### 2.3.1 Independent variables

Independent variables are those that are manipulated or varied during the experiment to observe their effects on machining outcomes, particularly surface roughness. The independent variables in this study include: (1) spindle tilt angles: 30°, 45°, and 60°; (2) depth of cut: 0.50 mm, 0.75 mm, 1.00 mm, 1.25 mm, and 1.50 mm; (3) feed rate: 45 mm/min, 69 mm/min, 108 mm/min, 168 mm/min, and 233 mm/min; (4) spindle speed: 144 rpm, 288 rpm, 388 rpm, 535 rpm, and 720 rpm.

#### 2.3.2 Dependent variable

The dependent variable is the variable that is observed or measured as a result of changes in the independent variables. In this study, the dependent variable is surface roughness (Ra), expressed in micrometres ( $\mu\text{m}$ ).

### 2.3.3 Controlled variables

Controlled variables are those that are kept constant throughout the experiment to avoid interference with the validity of the results. The controlled variables in this study include: (1) type and size of cutting tool: HSS end mill, 16 mm diameter; (2) material and dimensions of the workpiece: low-carbon steel with uniform dimensions; (3) type of milling process used: up milling and down milling; (4) clamping technique and feed direction, applied consistently across all tests.

### 2.4 Selection of testing parameters

Once all materials and equipment were prepared, the selection of testing parameters was carried out. The primary focus of the measurement was surface roughness, and the tests were divided into three groups based on the varied parameters, while the other two parameters were kept constant. Each test group was conducted at three spindle tilt angles: 30°, 45°, and 60°.

#### 2.4.1 Depth of cut variation

Variable parameter: depth of cut (0.50 mm–1.50 mm). Constant parameters: (1) feed rate: 108 mm/min, (2) spindle speed: 388 rpm.

#### 2.4.2 Feed rate variation

Variable parameter: feed rate (45 mm/min–233 mm/min). Constant parameters: (1) depth of cut: 0.50 mm, (2) spindle speed: 388 rpm.

#### 2.4.3 Spindle speed variation

Variable parameter: spindle speed (144 rpm–720 rpm). Constant parameters: (1) depth of cut: 0.50 mm, (2) feed rate: 108 mm/min.

### 2.5 Experimental procedure

The experimental procedure for collecting surface roughness data was carried out through the stages: (1) the workpiece was mounted and securely clamped on the machine table using a vise to ensure stability and positional accuracy during the machining process; (2) the spindle tilt was manually adjusted according to the specified angles in the experimental design: 30°, 45°, and 60°; (3) other machining parameters, such as spindle speed, feed rate, and depth of cut, were set based on the combinations planned during the experimental design phase; (4) the machining process was carried out using either the up milling or down milling method, depending on the specific testing scenario (Fig. 5); (5) after each cutting process, surface roughness (Ra) was measured using a surface roughness tester, measurements were taken at two different points on the machined surface of each sample, and the average of these two values was recorded as the final result (Fig. 6); (6) all measurement data were systematically recorded and then analyzed descriptively to observe patterns, trends, and the influence of each parameter on surface roughness.



Fig. 5. Milling process.

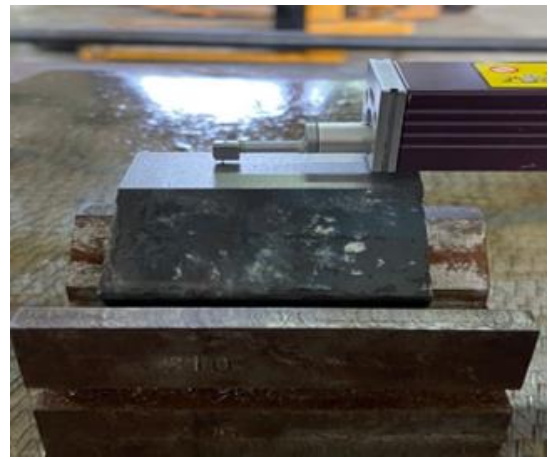


Fig. 6. Surface roughness measurement.

### 2.6 Data analysis and discussion

The data in this study were analyzed descriptively using a graphical visualization approach to interpret the effects of each machining process parameter, including spindle tilt, on the surface roughness (Ra) resulting from the milling process. Each Ra value was obtained as the average of two measurement points on the workpiece surface and served as the primary data for analysis.

The experimental data were organized into observation tables based on the tested parameter combinations and subsequently visualized in the form of graphs. Each graph illustrates the relationship between one independent variable, such as depth of cut, feed rate, or spindle speed and the corresponding surface roughness. The graphs were further categorized by spindle tilt angles (30°, 45°, and 60°) to facilitate the comparison of surface quality across different angular orientations.

The discussion was conducted by analyzing graphical patterns that indicate trends of increase, decrease, or fluctuation in surface roughness (Ra) due to changes in machining parameters. Each result was compared across the different spindle tilt levels to assess their respective impacts [9]. The graphs also helped to interpret the direct influence of spindle tilt on cutting direction, force distribution, and final surface finish. The interpretation was grounded in fundamental machining principles such as chip formation, cutting force behavior, and potential vibration effects [25].

## 3 Results and discussion

The results of this study indicate that machining parameters such as spindle tilt angle, feed rate, depth of cut, and spindle speed have a significant influence on the surface quality of milled workpieces, as measured by the surface roughness parameter (Ra). The experimental results are systematically presented in Table 1, Table 2, and Table 3, each representing surface roughness data under specific machining conditions with varying parameter combinations. The experiments were conducted using two primary milling techniques, up milling and down milling, at three spindle tilt angles: 30°, 45°, and 60°, along with a range of feed rates, depths of cut, and spindle speeds.

Based on the test data presented in Table 1, Table 2, and Table 3, it can be observed that increasing the spindle tilt angle, feed rate, and depth of cut tends to contribute to higher surface roughness (Ra) values in the milling process. This effect is primarily attributed to the increased mechanical load and cutting forces during machining, which result in a rougher surface finish on the workpiece. However, the test results also show that an increase in spindle speed has a positive impact on surface quality, as indicated by a decrease in surface roughness (Ra). This phenomenon occurs because higher spindle speeds help smooth the interaction between the cutting tool and the workpiece, reduce cutting forces per unit time, and facilitate the formation of thinner and more controlled chips [25]. Consequently, higher spindle speeds contribute to the formation of smoother and more uniform surface finishes.

Table 1. Surface roughness measurement data based on variations in spindle tilt angle and depth of cut

| $\Theta$<br>( $^{\circ}$ ) | FR<br>(m/min) | N<br>(rpm) | DOC<br>(mm) | Up milling                           |                                      |                              |                      | Down milling                         |                                      |                              |                      |
|----------------------------|---------------|------------|-------------|--------------------------------------|--------------------------------------|------------------------------|----------------------|--------------------------------------|--------------------------------------|------------------------------|----------------------|
|                            |               |            |             | Ra <sub>1</sub><br>( $\mu\text{m}$ ) | Ra <sub>2</sub><br>( $\mu\text{m}$ ) | Average<br>( $\mu\text{m}$ ) | Standar<br>deviation | Ra <sub>1</sub><br>( $\mu\text{m}$ ) | Ra <sub>2</sub><br>( $\mu\text{m}$ ) | Average<br>( $\mu\text{m}$ ) | Standar<br>deviation |
| 30                         | 108           | 388        | 0.50        | 0.357                                | 0.376                                | 0.367                        | 0.013                | 1.103                                | 1.202                                | 1.153                        | 0.070                |
| 30                         | 108           | 388        | 0.75        | 0.395                                | 0.404                                | 0.400                        | 0.006                | 1.292                                | 1.404                                | 1.348                        | 0.079                |
| 30                         | 108           | 388        | 1.00        | 0.431                                | 0.450                                | 0.441                        | 0.013                | 1.412                                | 1.449                                | 1.431                        | 0.026                |
| 30                         | 108           | 388        | 1.25        | 0.460                                | 0.494                                | 0.477                        | 0.024                | 1.516                                | 1.568                                | 1.542                        | 0.037                |
| 30                         | 108           | 388        | 1.50        | 0.531                                | 0.591                                | 0.561                        | 0.042                | 1.634                                | 1.669                                | 1.652                        | 0.025                |
| 45                         | 108           | 388        | 0.50        | 0.457                                | 0.459                                | 0.458                        | 0.001                | 1.319                                | 1.348                                | 1.334                        | 0.021                |
| 45                         | 108           | 388        | 0.75        | 0.491                                | 0.523                                | 0.507                        | 0.023                | 1.578                                | 1.596                                | 1.587                        | 0.013                |
| 45                         | 108           | 388        | 1.00        | 0.552                                | 0.571                                | 0.562                        | 0.013                | 1.627                                | 1.839                                | 1.733                        | 0.150                |
| 45                         | 108           | 388        | 1.25        | 0.574                                | 0.612                                | 0.593                        | 0.027                | 1.898                                | 1.951                                | 1.925                        | 0.037                |
| 45                         | 108           | 388        | 1.50        | 0.621                                | 0.665                                | 0.643                        | 0.031                | 2.150                                | 2.163                                | 2.157                        | 0.009                |
| 60                         | 108           | 388        | 0.50        | 0.571                                | 0.578                                | 0.575                        | 0.005                | 1.535                                | 1.541                                | 1.538                        | 0.004                |
| 60                         | 108           | 388        | 0.75        | 0.632                                | 0.646                                | 0.639                        | 0.010                | 1.760                                | 1.785                                | 1.773                        | 0.018                |
| 60                         | 108           | 388        | 1.00        | 0.677                                | 0.678                                | 0.678                        | 0.001                | 1.951                                | 2.098                                | 2.025                        | 0.104                |
| 60                         | 108           | 388        | 1.25        | 0.686                                | 0.703                                | 0.695                        | 0.012                | 2.151                                | 2.210                                | 2.181                        | 0.042                |
| 60                         | 108           | 388        | 1.50        | 0.710                                | 0.727                                | 0.719                        | 0.012                | 2.225                                | 2.397                                | 2.311                        | 0.122                |

Table 2. Surface roughness measurement data based on variations in spindle tilt angle and feed rate

| $\Theta$<br>( $^{\circ}$ ) | FR<br>(m/min) | N<br>(rpm) | DOC<br>(mm) | Up milling                           |                                      |                              |                      | Down milling                         |                                      |                              |                      |
|----------------------------|---------------|------------|-------------|--------------------------------------|--------------------------------------|------------------------------|----------------------|--------------------------------------|--------------------------------------|------------------------------|----------------------|
|                            |               |            |             | Ra <sub>1</sub><br>( $\mu\text{m}$ ) | Ra <sub>2</sub><br>( $\mu\text{m}$ ) | Average<br>( $\mu\text{m}$ ) | Standar<br>deviation | Ra <sub>1</sub><br>( $\mu\text{m}$ ) | Ra <sub>2</sub><br>( $\mu\text{m}$ ) | Average<br>( $\mu\text{m}$ ) | Standar<br>deviation |
| 30                         | 45            | 388        | 0.50        | 0.357                                | 0.336                                | 0.347                        | 0.015                | 0.507                                | 0.624                                | 0.566                        | 0.083                |
| 30                         | 69            | 388        | 0.50        | 0.392                                | 0.376                                | 0.384                        | 0.011                | 0.714                                | 0.862                                | 0.788                        | 0.105                |
| 30                         | 108           | 388        | 0.50        | 0.410                                | 0.415                                | 0.413                        | 0.004                | 1.336                                | 1.223                                | 1.280                        | 0.080                |
| 30                         | 168           | 388        | 0.50        | 0.435                                | 0.558                                | 0.497                        | 0.087                | 1.574                                | 1.435                                | 1.505                        | 0.098                |
| 30                         | 233           | 388        | 0.50        | 0.546                                | 0.698                                | 0.622                        | 0.107                | 1.851                                | 1.992                                | 1.922                        | 0.100                |
| 45                         | 45            | 388        | 0.50        | 0.406                                | 0.433                                | 0.420                        | 0.019                | 1.978                                | 2.058                                | 2.018                        | 0.057                |
| 45                         | 69            | 388        | 0.50        | 0.505                                | 0.519                                | 0.512                        | 0.010                | 2.122                                | 2.175                                | 2.149                        | 0.037                |
| 45                         | 108           | 388        | 0.50        | 0.545                                | 0.586                                | 0.566                        | 0.029                | 2.272                                | 2.378                                | 2.325                        | 0.075                |
| 45                         | 168           | 388        | 0.50        | 0.661                                | 0.676                                | 0.669                        | 0.011                | 2.382                                | 2.428                                | 2.405                        | 0.033                |
| 45                         | 233           | 388        | 0.50        | 0.723                                | 0.757                                | 0.740                        | 0.024                | 2.646                                | 2.687                                | 2.667                        | 0.029                |
| 60                         | 45            | 388        | 0.50        | 0.474                                | 0.504                                | 0.489                        | 0.021                | 1.944                                | 1.998                                | 1.971                        | 0.038                |
| 60                         | 69            | 388        | 0.50        | 0.515                                | 0.517                                | 0.516                        | 0.001                | 2.104                                | 2.256                                | 2.180                        | 0.107                |
| 60                         | 108           | 388        | 0.50        | 0.578                                | 0.592                                | 0.585                        | 0.010                | 2.322                                | 2.411                                | 2.367                        | 0.063                |
| 60                         | 168           | 388        | 0.50        | 0.611                                | 0.636                                | 0.624                        | 0.018                | 2.362                                | 2.481                                | 2.422                        | 0.084                |
| 60                         | 233           | 388        | 0.50        | 0.678                                | 0.749                                | 0.714                        | 0.050                | 2.505                                | 2.536                                | 2.521                        | 0.022                |

Table 3. Surface roughness measurement data based on variations in spindle tilt angle and spindle speed

| $\Theta$<br>( $^{\circ}$ ) | FR<br>(m/min) | N<br>(rpm) | DOC<br>(mm) | Up milling                           |                                      |                              |                      | Down milling                         |                                      |                              |                      |
|----------------------------|---------------|------------|-------------|--------------------------------------|--------------------------------------|------------------------------|----------------------|--------------------------------------|--------------------------------------|------------------------------|----------------------|
|                            |               |            |             | Ra <sub>1</sub><br>( $\mu\text{m}$ ) | Ra <sub>2</sub><br>( $\mu\text{m}$ ) | Average<br>( $\mu\text{m}$ ) | Standar<br>deviation | Ra <sub>1</sub><br>( $\mu\text{m}$ ) | Ra <sub>2</sub><br>( $\mu\text{m}$ ) | Average<br>( $\mu\text{m}$ ) | Standar<br>deviation |
| 30                         | 108           | 148        | 0.50        | 0.626                                | 0.647                                | 0.637                        | 0.015                | 1.325                                | 1.385                                | 1.355                        | 0.042                |
| 30                         | 108           | 288        | 0.50        | 0.502                                | 0.614                                | 0.558                        | 0.079                | 1.213                                | 1.376                                | 1.295                        | 0.115                |
| 30                         | 108           | 388        | 0.50        | 0.408                                | 0.572                                | 0.490                        | 0.116                | 1.191                                | 0.918                                | 1.055                        | 0.193                |
| 30                         | 108           | 535        | 0.50        | 0.320                                | 0.338                                | 0.329                        | 0.013                | 0.894                                | 0.847                                | 0.871                        | 0.033                |
| 30                         | 108           | 720        | 0.50        | 0.258                                | 0.338                                | 0.298                        | 0.057                | 0.887                                | 0.920                                | 0.904                        | 0.023                |
| 45                         | 108           | 148        | 0.50        | 0.720                                | 0.817                                | 0.769                        | 0.069                | 1.436                                | 1.471                                | 1.454                        | 0.025                |
| 45                         | 108           | 288        | 0.50        | 0.637                                | 0.667                                | 0.652                        | 0.021                | 1.309                                | 1.359                                | 1.334                        | 0.035                |
| 45                         | 108           | 388        | 0.50        | 0.613                                | 0.650                                | 0.632                        | 0.026                | 1.234                                | 1.335                                | 1.285                        | 0.071                |
| 45                         | 108           | 535        | 0.50        | 0.463                                | 0.499                                | 0.481                        | 0.025                | 1.208                                | 1.212                                | 1.210                        | 0.003                |
| 45                         | 108           | 720        | 0.50        | 0.433                                | 0.438                                | 0.436                        | 0.004                | 1.104                                | 1.125                                | 1.115                        | 0.015                |
| 60                         | 108           | 148        | 0.50        | 0.780                                | 0.876                                | 0.828                        | 0.068                | 1.705                                | 1.795                                | 1.750                        | 0.064                |
| 60                         | 108           | 288        | 0.50        | 0.710                                | 0.746                                | 0.728                        | 0.025                | 1.670                                | 1.690                                | 1.680                        | 0.014                |
| 60                         | 108           | 388        | 0.50        | 0.650                                | 0.686                                | 0.668                        | 0.025                | 1.400                                | 1.659                                | 1.530                        | 0.183                |
| 60                         | 108           | 535        | 0.50        | 0.557                                | 0.499                                | 0.528                        | 0.041                | 1.342                                | 1.451                                | 1.397                        | 0.077                |
| 60                         | 108           | 720        | 0.50        | 0.454                                | 0.478                                | 0.466                        | 0.017                | 1.314                                | 1.245                                | 1.280                        | 0.049                |

### 3.1 Data variability discussion

Based on the data in Tables 1–3, the standard deviation values in the surface roughness (Ra) measurements indicate the variability of results for each parameter combination. In Table 1 (variation of spindle tilt angle and depth of cut), the standard deviation for the up milling process ranges from 0.001–0.042  $\mu\text{m}$ , while for down milling it ranges from 0.009–0.150  $\mu\text{m}$ . The relatively small

variability in up milling indicates more stable surface quality. In contrast, the higher values in down milling, particularly at a 45° tilt angle and 1.00 mm depth of cut (0.150  $\mu\text{m}$ ) suggest process instability, likely due to inconsistent chip formation.

In Table 2 (variation of spindle tilt angle and feed rate), the standard deviation for up milling is in the range of 0.001–0.107  $\mu\text{m}$ , while down milling ranges from 0.022–0.107  $\mu\text{m}$ . The highest

standard deviation in up milling occurs at a 30° tilt angle and a feed rate of 233 m/min (0.107 μm), indicating that higher feed rates tend to increase surface variability. Visualizing these results with error bars would reveal longer error bars at higher feed rates, reflecting greater uncertainty in the measurements.

In Table 3 (variation of spindle tilt angle and spindle speed), the standard deviation for up milling ranges from 0.004–0.116 μm, while for down milling it ranges from 0.003–0.193 μm. The highest value occurs in down milling at a 30° tilt angle and 388 rpm spindle speed (0.193 μm), indicating substantial fluctuations in surface roughness, possibly due to the interaction between cutting speed and unstable chip formation.

Overall, low standard deviation values (<0.02 μm) indicate stable cutting conditions and consistent results. In contrast, high values (>0.10 μm) suggest factors that increase variability, such as vibration, initial tool wear, or chip flow disturbances. When visualized using graphs with error bars, conditions with high standard deviations would clearly display longer error bars, making it easier to identify parameter settings that produce less consistent results.

### 3.2 The influence of spindle tilt and depth of cut on surface roughness

To examine the influence of spindle tilt and depth of cut on surface roughness, reference can be made to Fig. 7 and Fig. 8. These figures illustrate the relationship between depth of cut and surface roughness in both up milling and down milling processes, as affected by variations in spindle tilt.

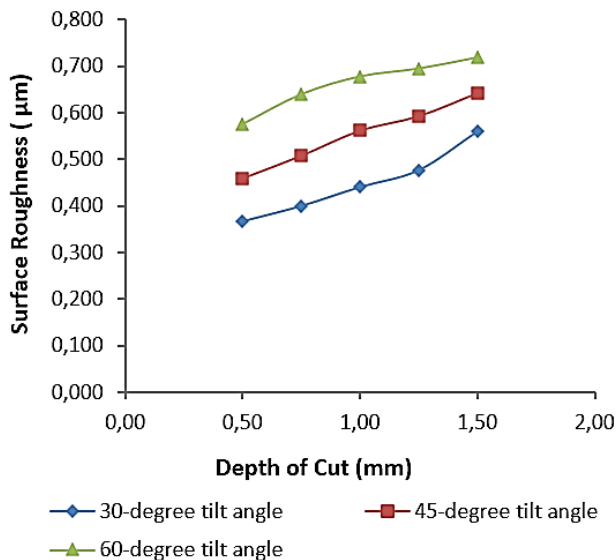


Fig. 7. Depth of cut vs surface roughness (up milling).

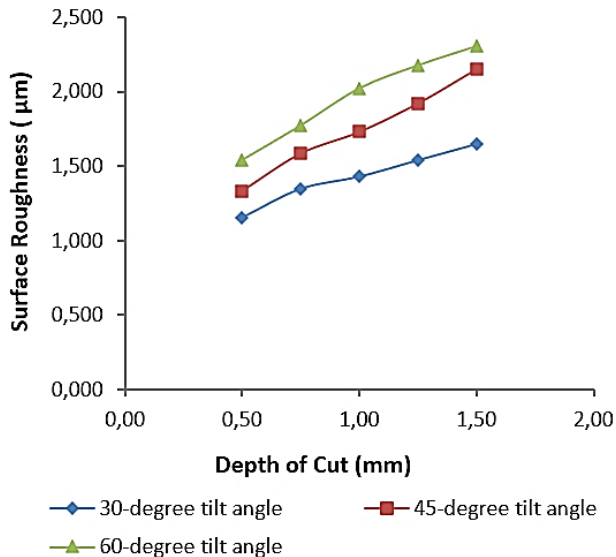


Fig. 8. Depth of cut vs surface roughness (down milling).

Based on the data analysis presented in the Fig. 7 and Fig. 8, it can be concluded that spindle tilt and depth of cut have a significant effect on surface roughness in the milling process. These two parameters directly influence the direction and magnitude of the cutting forces acting on the workpiece, which in turn determine the level of precision and the final surface quality of the machined part.

Spindle tilt is one of the key factors that directly affect the distribution direction of cutting forces on the workpiece surface. The greater the spindle tilt angle, the more unevenly the cutting forces are transmitted to the workpiece surface [1]. This condition can lead to vibration, chip instability, and micro-irregularities that increase surface roughness [9]. For instance, in Fig. 7, with a depth of cut of 0.50 mm and a spindle tilt angle of 30°, the surface roughness was recorded at 0.367 μm. However, when the spindle tilt was increased to 45° and 60°, the surface roughness values rose to 0.458 μm and 0.575 μm, respectively. A similar trend is also observed in Fig. 8 under the down milling configuration, where surface roughness increased from 1.153 μm at 30° tilt to 2.311 μm at 60°.

Meanwhile, the depth of cut has also been shown to have a significant impact on surface roughness. As the depth of cut increases, the volume of material that must be removed becomes larger, resulting in a substantial rise in cutting forces [9]. This increase in force intensifies the contact pressure between the cutting tool and the workpiece surface, leading to higher friction, localized heating, and potential plastic deformation on the surface, all of which contribute to a decline in surface quality [26]. For example, at a spindle tilt angle of 30°, increasing the depth of cut from 0.50 mm to 1.50 mm raised the surface roughness from 0.367 μm to 0.561 μm under up milling conditions (Fig. 7), and from 1.153 μm to 2.311 μm under down milling conditions (Fig. 8).

The interaction between spindle tilt and depth of cut also demonstrates a mutually reinforcing relationship in increasing surface roughness [27]. The negative effect of increasing the depth of cut becomes more pronounced when combined with a large spindle tilt angle [9]. This means that in machining configurations with a high tilt angle, greater depths of cut exacerbate overall process instability, which directly impacts the formation of rougher surfaces. Such parameter combinations should be avoided if the primary goal is to achieve low surface roughness levels [28].

In general, the experimental results indicate that increasing spindle tilt and depth of cut tends to have a negative effect on the surface quality of milled components [29]. Selecting appropriate parameters is not only essential to avoid excessive surface roughness but also critical for maintaining tool life, machining efficiency, and the structural integrity of the workpiece [30]. Therefore, optimization approaches in machining processes should take into account the interactions among these key parameters to achieve a balanced outcome between productivity and surface quality [31].

### 3.3 The influence of spindle tilt and feed rate on surface roughness

The influence of spindle tilt and feed rate on surface roughness can be analyzed through Fig. 9 and Fig. 10. These figures illustrate the relationship between variations in feed rate and surface roughness values during up milling and down milling processes, as affected by different spindle tilt angles. This visualization provides a clearer understanding of how the combination of feed rate and spindle tilt impacts the surface quality of the machined workpiece.

Based on the data analysis presented in Fig. 9 and Fig. 10, spindle tilt and feed rate have been shown to significantly affect surface roughness in milling processes, both under up-milling and down-milling conditions. These two parameters directly influence cutting forces, pressure distribution, and friction between the cutting tool and the workpiece, all of which collectively impact the final surface quality [32]. An increase in spindle tilt angle tends to lead to higher surface roughness values [9]. This occurs because

larger tilt angles result in greater and often uneven cutting forces being transmitted to the workpiece surface, frequently causing vibration and instability during the cutting process [25]. For instance, in Fig. 9, which depicts up milling conditions, the surface roughness at a spindle tilt of 30° and a feed rate of 108 mm/min was lower compared to the roughness observed at tilt angles of 45° and 60°. Similarly, in Fig. 10 (down milling), at a feed rate of 233 mm/min, surface roughness increased significantly at a tilt angle of 60°, indicating that a larger tilt angle deteriorates surface quality, particularly at higher feed rates.

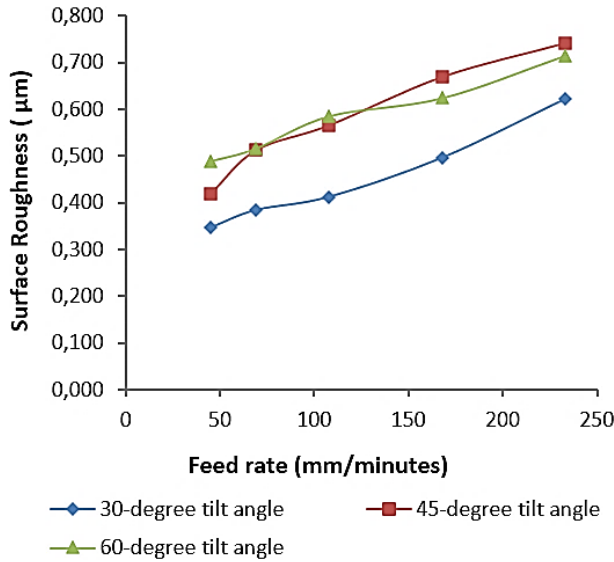


Fig. 9. Feed rate vs surface roughness (up milling).

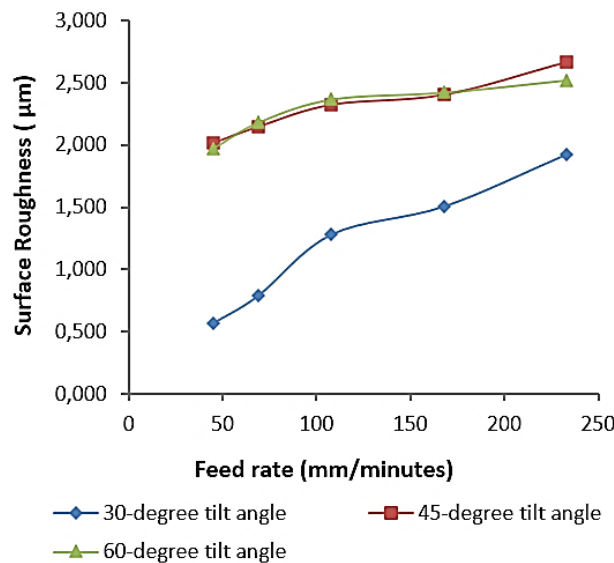


Fig. 10. Feed rate vs surface roughness (down milling).

Feed rate also exhibited a consistent influence on increasing surface roughness. Based on the data presented in Fig. 9 and Fig. 10, it can be observed that higher feed rates lead to higher roughness values, regardless of the spindle tilt angle. For example, at a tilt angle of 30°, surface roughness increased from approximately 0.347 µm at a feed rate of 45 mm/min to 0.622 µm at 233 mm/min. This is attributed to the intensified interaction between the cutting tool and the workpiece, which generates greater cutting forces and friction, while also reducing the cutting time per unit length—factors that contribute to poorer surface formation [33]. A similar phenomenon was observed under down milling conditions, where each increase in feed rate resulted in a significant rise in surface roughness across all spindle tilt variations [34].

In addition to the individual effects of each parameter, there is also a significant interaction between spindle tilt and feed rate. The negative impact of increasing spindle tilt on surface roughness becomes more pronounced when combined with a high feed rate

[35]. In other words, the simultaneous use of a large tilt angle and a high feed rate tends to exacerbate surface quality deterioration [36]. For instance, at a spindle tilt of 60° and a feed rate of 233 mm/min, the surface roughness increased drastically, reflecting the cumulative effect of high cutting forces and friction on the workpiece surface [9].

Based on the results of the analysis, it can be concluded that increasing spindle tilt and feed rate generally has a negative effect on surface roughness [37]. Therefore, to achieve a smoother surface finish, it is essential to select optimal machining parameters specifically, by employing a small spindle tilt angle and a low to moderate feed rate [38]. Understanding the influence and interaction of these two parameters is crucial for optimizing the machining process, improving efficiency, and maintaining the quality and precision of the final product [39].

### 3.4 The influence of spindle tilt and spindle speed on surface roughness

The influence of spindle tilt and spindle speed on surface roughness can be examined through Fig. 11 and Fig. 12. These figures illustrate how variations in spindle rotational speed affect the surface roughness in up milling and down milling processes under different spindle tilt conditions. This data presentation provides a more comprehensive insight into the combined effects of spindle tilt angle and spindle speed on the final surface quality of the workpiece, particularly through changes in cutting force characteristics and the stability of the interaction between the cutting tool and the machined material.

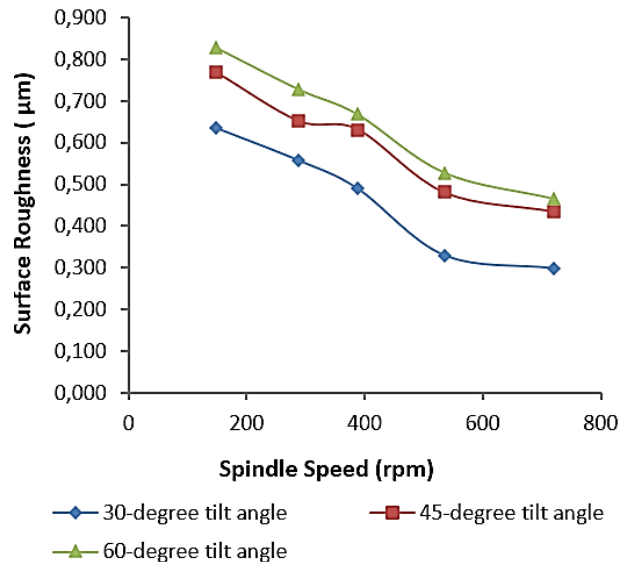


Fig. 11. Spindle speed vs surface roughness (up milling).

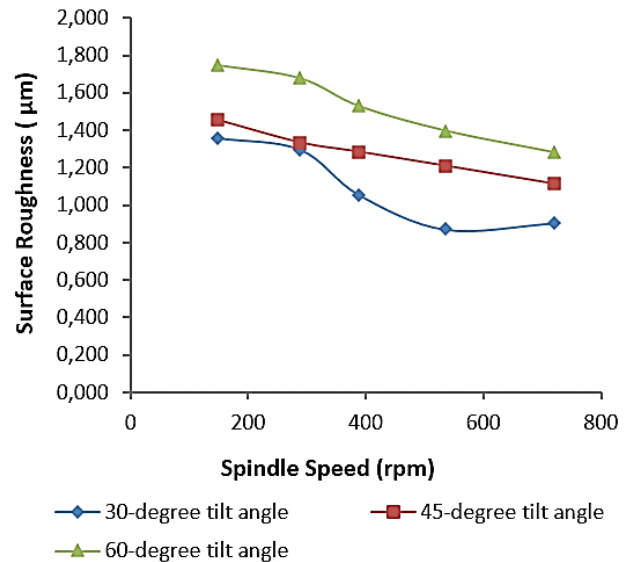


Fig. 12. Spindle speed vs surface roughness (down milling).

The data analysis presented in Fig. 11 and Fig. 12 indicates that spindle tilt and spindle speed have a significant impact on the surface roughness produced in the milling process. These two parameters influence the characteristics of cutting forces, the contact between the tool and the workpiece, and the overall stability of the machining process, all of which directly determine the final surface quality.

Spindle tilt has been shown to have a positive correlation with increased surface roughness. In both up milling and down milling processes, increasing the spindle tilt angle leads to higher surface roughness values. For instance, in the up milling process at a spindle speed of 148 rpm, the surface roughness was approximately 0.637  $\mu\text{m}$  at a 30° tilt, but increased to 0.828  $\mu\text{m}$  when the tilt angle was raised to 60°. A similar trend was observed in down milling, where surface roughness rose from 1.325  $\mu\text{m}$  to 1.705  $\mu\text{m}$  under the same tilt angles and spindle speed. An increase in spindle tilt enlarges the cutting contact angle, which results in uneven distribution of cutting forces and increased vibration during machining, ultimately producing a rougher surface finish [40].

On the other hand, spindle speed exhibits an opposite effect. An increase in spindle speed tends to reduce surface roughness. This can be attributed to the decreased contact time between the cutting tool and the workpiece at higher rotational speeds, resulting in smoother and more stable cutting [41]. For instance, at a spindle tilt of 30°, the surface roughness in up milling decreased from 0.637  $\mu\text{m}$  at 148 rpm to 0.298  $\mu\text{m}$  at 720 rpm. A similar reduction was observed in down milling, where at a 60° tilt and 720 rpm, surface roughness dropped to approximately 1.104  $\mu\text{m}$ . However, this reduction remains significantly influenced by the spindle tilt angle, which continues to play a dominant role in increasing roughness.

These results also indicate an interaction between spindle tilt and spindle speed. Although higher spindle speeds generally lead to reduced surface roughness, the adverse effects of a large tilt angle remain dominant [42]. For instance, at a high speed of 720 rpm, the machined surface at a 60° tilt was still rougher than that at a 30° tilt, both in up milling and down milling operations. This suggests that high spindle speed alone is not sufficient to counteract the negative impact of increased spindle inclination on surface roughness.

Based on these findings, it can be concluded that an optimal combination of spindle tilt angle and spindle speed is crucial to achieving high surface quality. To produce a smoother surface finish, it is recommended to use a smaller spindle tilt angle in combination with a higher spindle speed [25]. Selecting the appropriate machining parameters not only enhances process efficiency but also minimizes surface deformation and extends the tool's service life [43].

Furthermore, it should be noted that cutting tool wear or edge degradation may be a contributing factor to variations in surface roughness, particularly in tests conducted repeatedly. Such wear can lead to a decline in cutting quality, an increase in cutting forces, and alterations in the chip formation mechanism, ultimately resulting in higher surface roughness [44]. Over time, progressive wear may also cause vibration, excessive heat generation, and material adhesion on the cutting edge, all of which further exacerbate the deterioration of surface finish [45].

### 3.5 Comparison of surface roughness between up milling and down milling

Based on the data presented in Table 1, Table 2, and Table 3, it can be observed that surface roughness (Ra) in milling processes is significantly influenced by several key parameters, namely spindle tilt angle, feed rate, depth of cut, and spindle speed. The measurement results indicate a notable difference in the surface quality of the workpiece between up milling and down milling, depending on the combination of parameters applied.

In up milling, the surface roughness tends to be lower compared to down milling under similar machining conditions. For example,

at a depth of cut of 0.50 mm, a feed rate of 108 m/min, and a spindle tilt angle of 30°, the surface roughness in up milling was recorded at 0.367  $\mu\text{m}$ , whereas in down milling it reached 1.153  $\mu\text{m}$ . This suggests that the cutting direction opposite to the feed direction in up milling produces a more stable and smoother surface finish [46].

Table 2 shows that as the feed rate increases, surface roughness tends to rise in both milling processes. For instance, at a feed rate of 233 m/min and a spindle tilt angle of 30°, surface roughness in up milling increased to 0.622  $\mu\text{m}$ , while in down milling it reached 1.922  $\mu\text{m}$ . This indicates that higher feed rates lead to greater cutting forces and friction, resulting in a rougher surface finish [47]. Meanwhile, Table 3 demonstrates that increasing the spindle speed from 148 rpm to 720 rpm generally reduces surface roughness. In up milling at 720 rpm, the surface roughness was recorded at only 0.298  $\mu\text{m}$ , while in down milling, it was 1.115  $\mu\text{m}$ . This suggests that higher spindle speeds reduce the contact time between the cutting tool and the workpiece, producing a smoother machined surface. However, the effectiveness of spindle speed is still influenced by other parameters such as spindle tilt angle and feed rate [25].

In general, up milling provides better surface quality compared to down milling. This advantage is particularly evident under machining conditions involving a small spindle tilt angle, low feed rate, and high spindle speed [48]. The superior performance of up milling is attributed to the lighter cutting forces and more stable chip formation. Conversely, while down milling is efficient in material removal, the cutting force that moves in the same direction as the feed tends to increase the risk of surface irregularities and higher roughness values [49]. Therefore, to achieve an optimal surface finish, the selection of machining method and operating parameters must align with the intended purpose of the process. Up milling is a more suitable choice when a smoother and more precise surface is required, especially in applications that demand tight surface tolerance [1].

## 4 Conclusions

This study examines the effect of spindle tilt and machining parameters which are feed rate, depth of cut, and spindle speed, on surface roughness in milling operations using a Knuth UFM 2 universal milling machine. A systematic experimental approach was applied, varying parameters to assess their influence on surface quality. Results indicate that higher spindle tilt, feed rate, and depth of cut generally increase surface roughness, while greater spindle speed reduces it, producing smoother surfaces. The optimal result was obtained in the first up-milling test with a spindle inclination of 30°, feed rate of 108 m/min, spindle speed of 720 rpm, and depth of cut of 0.50 mm, achieving a surface roughness (Ra) of 0.258  $\mu\text{m}$ . By contrast, increasing spindle tilt from 30° to 60° raised roughness by 95.91%, increasing depth of cut from 0.50 mm to 1.50 mm raised roughness by 52.86%, and increasing feed rate from 45 m/min to 233 m/min raised roughness by 79.25%. Conversely, increasing spindle speed from 148 rpm to 720 rpm reduced Ra by 99.81%. Interactions among these parameters also affect surface quality and tool life, making optimal parameter selection essential for achieving precise, efficient, and sustainable machining.

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