

## Effects of Workpiece Surface and Cutting Parameters on the Finished Surface Quality in Turning Based on Finite Element Method

Ngoc The Quang Ho<sup>1,2</sup>, Thanh Trung Do<sup>1,\*</sup>

<sup>1</sup> Faculty of Mechanical Engineering, HCMC University of Technology and Education, Vietnam

<sup>2</sup> Faculty of Engineering and Technology, Nguyen Tat Thanh University, Vietnam

\*Corresponding author. Email: [trungdt@hcmute.edu.vn](mailto:trungdt@hcmute.edu.vn)

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### ABSTRACT

Turning is a traditional and widely used machining process in the manufacturing industry. The finished surface quality is one of the most important factors in determining the quality of the product and the effectiveness of the machining process. The surface quality is affected by several factors such as workpiece surface, cutting parameters and tool stiffness. Also, the finite element method is a powerful tool to analyze these factors and optimize the process parameters to achieve the desired surface finish. Therefore, in this study, the different values of wavelength ( $s$ ), cutting speed ( $v$ ), cutting feed ( $f$ ) and stiffness of toolholder ( $K_x$ ) were considered by using simulation method. Then, the surface roughness values ( $R_z$ ) were determined from the different between the average value of the five tallest profile peak height and the average value of the five deepest profile valley in the finished surface. The results showed that the cutting feed was a main parameter that effected on the surface roughness ( $R_z$ ) in the metal turning process. Also, the optimal value of surface roughness was achieved when  $s = 0.05$  mm,  $f = 0.3 - 0.4$  mm/rev,  $K_x = 4 - 6$  e8N/m and  $v = 190$  m/min. The findings of this study can be helpful in selecting the surface quality of the workpiece, determining the sequence of machining steps and choosing the cutting parameters to achieve both high productivity and the desired surface quality of turning products.

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## 1. Introduction

Turning is a traditional machining process that involves rotating a workpiece and using a reciprocating tool to remove material and create the desired shape. It is often used to manufacture cylindrical parts including the shaft, roller bearing, pulley, etc. The quality of finished parts produced by turning is evaluated using several criteria, including dimensional accuracy, relative position of surfaces and surface roughness. Among these, the surface roughness is a significant concern due to its impact on the aesthetics and workability of the parts [1]-[3]. The surface roughness of a finished machined part is formed according to several factors. During the cutting process, a mechanical collision occurs between the rotating workpiece and the reciprocating tool, generating cutting force. This force includes the force and jet on the workpiece and the tool and mainly depends on the thickness of the cutting layer. Additionally, the cutting depth also depends on the workpiece surface, which is not always completely flat and can have undulations. As a result, the cutting force changes over time. Furthermore, the tool and the toolholder are not completely rigid and may deform during the machining process, causing a change in the relative position of the workpiece and the tool [4]. This can lead to an increase in the surface undulation of the finished part and a decrease in the surface quality of the part. However, the surface roughness of the finished product cannot be solely attributed to the above factors. It can also be influenced by the material properties, cutting parameters and tool geometry, among others.

In the turning process, there are two types of undulating waves: a surface undulating wave of the workpiece and an oscillating wave of the tool. The specific case of velocity determines whether there will be the same phase ( $\theta = 0^0$ ) or different phase ( $\theta \neq 0^0$ ) [5]. Consequently, the cutting speed affects the surface quality of the finished part. It is challenging to determine the optimal speed parameter that

minimizes the different phase and change in cutting depth while maintaining tool stability. The surface quality of the finished part depends on the oscillation process that alters the relative position between the workpiece and the tool. To enhance the surface quality of the final product, the tool and the workpiece should remain stable.

There are many studies conducted to identify the factors that affect the stability of both the workpiece and the tool. These studies also explore measures that can be taken to increase stability, which in turn, improves the surface quality of the workpiece. Additionally, there has been significant research conducted to understand the impact of various factors on tool vibration. *R. Mahdavinejad* analyzed the stability of the system of turning technology by the finite element method with ANSYS software. This research has described the vibration phenomenon of the machine, tool, workpiece and has built the stability lobes. It showed that the natural frequencies and vibration modes shape of the model in chuck-center with and without tailstock cases could be determined [6]. *M. S. Hajmohammadi and M. R. Movahhedy* conducted a study on the effects of temperature on the vibration process during turning, particularly the friction, plasticity, heat formation and damping. The study found that temperature changes result in changes to the stability lobe diagram [7]. In a separate study, *C. Brecher et al.* developed a 3D simulation model for turning, which incorporated cutting force and cutting process simulations based on the workpiece and tool geometry parameters. It concluded that the cutting with defined and undefined cutting edges, as well as sheet and bulk metal forming, were indeed key processes in the manufacturing industry that enable the creation of a wide variety of metal parts [8]. Also, some researchers have conducted experiments to compare and adjust parameters between simulated and experimental models to determine the characteristics of vibration phenomena in turning [1], [5]. *A. K. Parida and K. Maity* utilized Deform software to simulate hot turning for Inconel 625 with varying cutting parameters such as temperature and speed. The study found that increasing hot turning temperature reduces cutting force, limits tool wear and increases tool life. At 600 °C, the chip will form continuously rather than discontinuous chip when turning at room temperature. Additionally, the study concluded that the cutting force and chip formation process between simulation and experimental results are similar [9]. *O. B. Abouelatta and J. Madl* predicted the surface quality of machined parts based on cutting technology parameters and tool vibration during turning. The study used experimental planning tools such as SPSS and MATLAB to establish regression equations and define the effective relationship between tool feed, depth of cutting and surface quality of the part after machining. It could be useful in predicting roughness parameters as a function of cutting parameters and tool vibrations [10], [11]. Regarding the techniques for controlling the cutting parameters, numerous studies have been conducted utilizing PID, Fuzzy control theory, Taguchi's approach and neural networks to optimize the technological parameters and achieve the best product quality during machining [12]-[14].

However, there have been very few studies conducted on the characteristics of workpiece surfaces and the technological parameters that affect the surface of the part using the finite element method. In practical production, it is crucial to determine the number of machining layers and the technological parameters of the final machining layer to achieve the desired surface gloss of the workpiece. Therefore, this study aims to investigate the effects of surface undulations of the workpiece and cutting parameters on the surface roughness of the part after machining. The undulation characteristics of the workpiece surface are described through parameters such as undulating wavelengths. This examination provides a basis for technology engineers to select a set of parameters, such as the quality of the workpiece surface, spindle speed, tool feed and stiffness of the toolholder, to achieve the best surface quality of the part after machining.

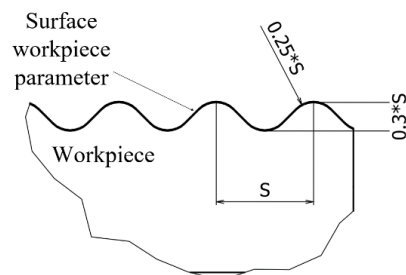
## 2. Numerical method

In turning process, the cutting operation is essentially a three-dimensional model with a complex technological system of machine, tool, workpiece and jig. However, in this study, due to the cost, convenience and purpose of only surface undulation, the simple case of two-dimensional orthogonal cutting is considered basing on the numerical method. The material is removed by a cutting edge that is perpendicular to the direction of relative tool-workpiece motion [15]. The numerical values for the workpiece, tool, and cutting parameters can be found in Table 1. The selection of cutting parameters is based on the manufacturer's recommendations for machining aluminum material. In mechanical

machining, there are several criteria for evaluating the quality of the product, such as dimensional tolerance, surface roughness and correlation errors between surfaces. The finished surface criterion is also crucial as it affects the assembly characteristics and aesthetic appeal of product. There are two common parameters, Ra and Rz, used to measure surface roughness. In this study, Rz is chosen because it represents the characteristic that can be easily determined from the surface deformation after cutting. The finite elemental method with the cutting model, as Fig. 1, is considered for examining the surface roughness values (Rz) that is the different between the average value of the five tallest profile peak height and the average value of the five deepest profile valley in the finished surface. The material of tool is carbide with the absolute hard model and the geometrical parameters of tool are constant values of the rake angle, relief angle and cutting edge radius. The machining material is aluminum Al\_6061 with the model of elastic deformation and plastic deformation by Johnson Cook model that relates to the mechanical parameters of materials and the geometrical parameters of the tool [16], [17]. In this study, the cutting parameters are considered by varying the cutting speed in range 90 - 290 m/min, the cutting feed in range 0.1 - 0.5 mm/rev and depth of cut 1 mm. Moreover, the surface quality after machining is depending not only on the stiffness of workpiece but also on the stiffness of toolholder [18]. Moreover, the stiffness values of the toolholder range from 2 to 10 e8 N/m, which are determined through the elastic deformation of the toolholder when clamped in a toolholder, with one end fixed and the other end free. The wavelength values of workpiece are from 0 to 0.2 mm (Fig. 1) for considering the effects of workpiece and tool on the surface roughness in turning process [19].

**Table 1.** Workpiece, tool and cutting parameters.

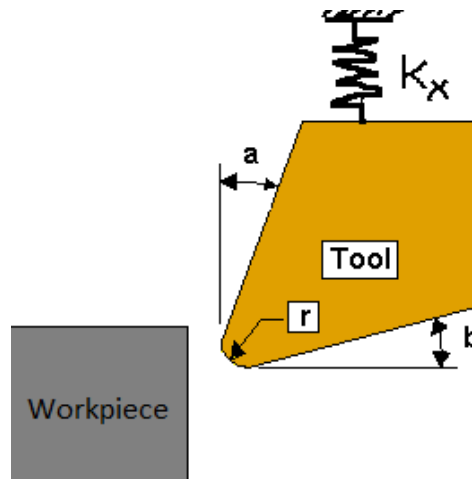
Parameters		Value
Workpiece	Material	Al_6061
	Height	2 mm
	Length	5 mm
Tool	Rake angle	5°
	Relief angle	10°
	Cutting edge radius	0.2 mm
	Material	Carbide
Cutting	Speed (v)	90 - 290 m/min
	Feed (f)	0.1 - 0.5 mm/rev
	Depth of cut	1 mm



**Figure 1.** The model of workpiece with the surface undulation.

In metal cutting mechanical machining, engineers always have to choose the material, technological process and process parameters in order to achieve the best product quality. The surface quality of the machined part is a critical factor and it is influenced by various factors, including cutting parameters such as cutting speed, cutting depth and tool clamping method, which are related to the tool shank's rigidity, as well as the choice of workpiece surface quality or the selection of cutting step in turning. Therefore, this study focuses on optimizing these four parameters. To synthesize multifactorial influencing factors, the Taguchi method is used with four parameters including the wavelength (s), the cutting feed (f), the cutting speed (v) and the tool stiffness (Kx). The Taguchi method is a strong

experimental design method with the number of technological parameters and their levels included in the experimental design matrix are large, but the number of experiments is less. This saves the cost of experimental materials and the experimental time. In addition, the parameters included in the experimental design matrix can be either quantitative or qualitative and the levels of these parameters can be arbitrarily selected. This would be impracticable in some traditional experimental designs. On the other hand, the experimental design matrices are available, so it is very convenient for application. The advantages of this method have resulted in its popular application in practice. Taguchi method uses orthogonal series of numbers in experimental planning thus studying the effect of parameters on a certain selected response and then quickly adjusts exactly the parameters to the fastest optimization. In this study, because the surface roughness of the workpiece after machining needs to be low, the signal/noise ratio is calculated with each factor is considered for 5 levels and the Taguchi L25 model (25 experimental levels) is selected [6], [19], [20].

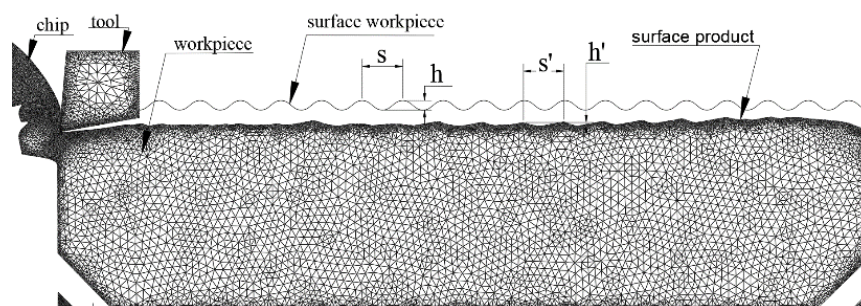


**Figure 2.** The model of tool with the stiffness  $K_x$ .

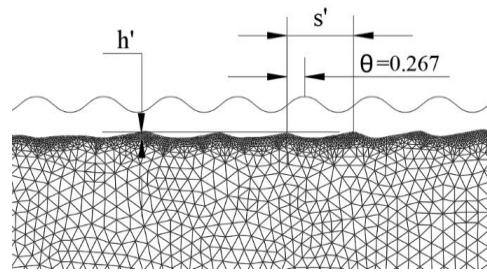
### 3. Results and Discussion

#### 3.1. The surface undulation

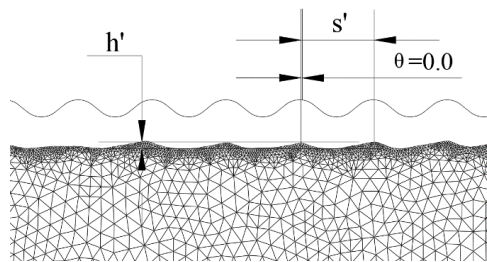
Figure 3 displayed the simulation result that showed the surface waves of the workpiece and the machined part (product) with a fluctuation wavelength of 0.2 mm. The cutting depth changed depending on the surface waves and the tool's stiffness. In there,  $s$  represented the surface wavelength of the workpiece,  $s'$  represented the surface waves of the machined part after processing and  $h$  represented the height difference of the machined part after processing. The surface roughness could be determined based on the value of  $h$ . During the machining process, the surface roughness of the workpiece and the tool's stiffness affected the phase difference ( $\theta$ ) between the surface waves of the workpiece and the machined part, which was described in Figure 4 ( $\theta \neq 0$ ) and Figure 5 ( $\theta = 0$ ). This phase difference affected the surface roughness of the machined part [1], [5]. In general, the surface wavelength was one of the critical factors that affected the surface quality of the machined part. Therefore, this parameter was studied along with the cutting parameters and the tool's stiffness.



**Figure 3.** The surface waves of the workpiece and the machined part.



**Figure 4.** The phase difference between the surface waves of the workpiece and the machined part with  $\theta \neq 0$ .



**Figure 5.** The phase difference between the surface waves of the workpiece and the machined part with  $\theta = 0$ .

### 3.2. Optimization of cutting parameters

The Taguchi method had been used in this study to optimize the cutting parameters for achieving the best surface roughness while reducing the calculation cost and simulation time. The results of the Taguchi study with L25, as presented in Table 2, indicated that the surface roughness ( $R_z$ ) was influenced by different cutting parameter values during the machining process. To evaluate the impact of these parameters, the signal-to-noise ratio (S/N) had been calculated and presented in Table 3. The S/N ratio provided an estimate of the degree of impact of each parameter on the surface roughness. It could be inferred that the feed had the greatest effect on the surface roughness. This meant that increasing the feed rate would result in higher surface roughness. On the other hand, increasing the other parameters (such as cutting speed and depth of cut) also increased the surface roughness, but the effect level was small, indicating a small gradient. Overall, the Taguchi method had proved to be an effective approach for optimizing the cutting parameters and achieving the best surface roughness. The results of the study provided valuable insights into the impact of different parameters on the surface roughness and could be used to inform future machining processes for achieving optimal surface quality.

**Table 2.** Taguchi table values.

No.	s (mm)	f (mm/rev)	v (m/min)	Kx (e8 N/m)	Rz (mm)
1	0	0.1	90	2	0.050
2	0	0.2	140	4	0.062
3	0	0.3	190	6	0.095
4	0	0.4	240	8	0.197
5	0	0.5	290	10	0.200
6	0.05	0.1	140	6	0.025
7	0.05	0.2	190	8	0.053
8	0.05	0.3	240	10	0.099
9	0.05	0.4	290	2	0.056

10	0.05	0.5	90	4	0.097
11	0.1	0.1	190	10	0.054
12	0.1	0.2	240	2	0.171
13	0.1	0.3	290	4	0.104
14	0.1	0.4	90	6	0.116
15	0.1	0.5	140	8	0.224
16	0.15	0.1	240	4	0.090
17	0.15	0.2	290	6	0.102
18	0.15	0.3	90	8	0.093
19	0.15	0.4	140	10	0.103
20	0.15	0.5	190	2	0.205
21	0.2	0.1	290	8	0.200
22	0.2	0.2	90	10	0.126
23	0.2	0.3	140	2	0.139
24	0.2	0.4	190	4	0.111
25	0.2	0.5	240	6	0.124

**Table 3.** Response table for S/N ratio.

Level	s	f	V	Kx
1	19.74	23.66	20.72	19.46
2	24.59	20.57	21.21	20.82
3	18.41	19.59	20.83	21.83
4	18.98	19.34	17.72	17.45
5	17.27	15.83	18.50	19.43
Delta	7.32	7.83	3.50	4.39
Rank	2	1	4	3



**Figure 6.** Main effects plot for S/N ratio.

Figure 6 illustrated that the feed rate factor ( $f$ ) had the greatest impact on the surface undulation. The larger the feed rate, the greater the surface undulation, but the level of effect varied at different stages [2], [10]. The effect was particularly significant in the range of 0.1 - 0.2 mm and 0.4 - 0.5 mm (large slope). This could be explained by the fact that at small feed rates, there was a high ratio of undulating and flat material, resulting in a high change in the shear load value. On the other hand, at a feed rate of 0.5, the higher shear load led to significant deformation and instability of the toolholder. However, the level of effect was minimal in the range of  $f = 0.3 - 0.4$ . The undulating wave on the surface was the second factor affecting surface quality. It suggested that the larger the undulating wave of the workpiece surface, the worse the surface quality. However, the level of effect was uncertain due to the phase difference of the undulating wave compared to the oscillation phase of the tool presented in the introduction. Nevertheless, in this experiment, it was found that the wavelength  $s = 0.05$  produced the best surface quality of the finished products.

The deformation and stiffness of the tool were the third factors to consider. Ideally, no oscillation would have given the best surface quality. However, in practice, the toolholder was subject to deformation and oscillation. When oscillating, the quality of the workpiece surface depended on the frequency of the toolholder and the undulating wave. Therefore, there was no linear trend in this relationship. However, in this experiment, the best surface quality for the finished product was obtained with the  $K_x$  value between 4 - 6 e8N/m. Similarly, cutting speed was the fourth factor in the group of factors. Based on the graph, the cutting speed mostly affected the surface roughness in the range of 190 - 240 m/min. The graph showed that the best surface quality was obtained at 90 m/min. This was because the smaller the cutting speed, the more stable the shear load.

#### 4. Conclusions

The research aimed to determine the surface quality of a machined part by measuring its surface undulation through the evaluation of roughness surface ( $R_z$ ) after simulation and specification. The analysis established a relationship between the surface undulating factors of the workpiece and cutting parameters, utilizing the Taguchi model to predict the surface quality of products.

Among the influencing factors, it was found that the cutting feed factor had the greatest impact on the finished surface roughness. Through the simulation method, the influential factors affecting the surface quality of the product were investigated. The results are consistent with previous theoretical and experimental studies.

Importantly, the use of simulation data has notable advantages in terms of time, cost and the potential for expanding research to other parameters. These findings can aid technology engineers in selecting the appropriate feed rate for turning operations to achieve the desired surface quality of the part after machining. It is recommended to use a cutting feed smaller than 0.3 mm, resulting in an  $R_z$  value of approximately 0.05 mm.

Furthermore, these study results provide technologists with a foundation for selecting optimal technological parameters, such as cutting depth and the number of cuts, to achieve the most desirable surface quality and productivity of parts by utilizing the simulated surface quality outcome.

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**Ho Ngoc The Quang** graduated with a Bachelor of Science in Mechanical Engineering from Ho Chi Minh City University of Technology and Education in 2004. He then received a Master's degree in Mechanical Engineering in 2007 and is currently a PhD candidate at the same institution. In addition, he is currently a lecturer in the Faculty of Engineering and Technology at Nguyen Tat Thanh University in Ho Chi Minh City, Vietnam. His research areas include mechanical engineering, machine design, numerical simulation and experimental methods. Email: [quanghnt.ncs@hcmute.edu.vn](mailto:quanghnt.ncs@hcmute.edu.vn)



**Do Thanh Trung** received his B.S. degree in Mechanical Engineering from Ho Chi Minh City University of Technology and Education, Vietnam on March 2000. He then received his M.S. and Ph.D. degrees from Yeungnam University, Korea on August 2005 and August 2009, respectively. Between September 2009 and July 2010, he was also a post-doctoral at Yeungnam University, Korea. He is currently an Associate Professor at the Faculty of Mechanical Engineering at Ho Chi Minh City University of Technology and Education, Vietnam. His research interests focus on numerical and experimental manufacturing processes. Email: [trungdt@hcmute.edu.vn](mailto:trungdt@hcmute.edu.vn)