Analysis of the Influence of Spindle Speed and Feed Rate on the Surface Quality of SS400 Steel in the CNC Lathe Machining Process Using the Taguchi Method

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Abstract

The CNC lathe machining process is one of the main technologies in the modern manufacturing industry, as it enables the production of components with high precision and efficient processing time. A CNC lathe forms the outer and inner surfaces of a workpiece by rotating the material while bringing it into contact with a cutting tool. Among the key parameters affecting machining performance, spindle speed and feed rate play a crucial role determining the surface quality of the machined part. However, previous studies still show inconsistency in defining the optimal parameter combination to achieve the best surface finish for SS400 steel, which is widely used in the construction and automotive industries. This inconsistency indicates a research gap that requires further investigation through controlled experimental analysis focusing on the material characteristics of SS400 steel using a systematic optimization approach. This study aims to analyze influence of spindle speed and feed rate variations on the surface quality of SS400 steel in the CNC lathe machining process using Taguchi method. The experiment was conducted on a CNC Lathe Liouy Hsing 450 machine using a WNMG-type cutting tool as a fixed variable. The spindle speeds were set at 800, 1000, and 1200 revolutions per minute (rpm), while the feed rates were varied at 0.1, 0.2, and 0.3 millimeters per minute (mm/min). Data were collected through observation and documentation methods and analyzed using Microsoft Excel to determine the average surface roughness value. The results showed that feed rate has a more significant influence than spindle speed on surface roughness. The optimal condition was obtained at a spindle speed of 1000 rpm and a feed rate of 0.1 mm/min, producing the smoothest surface roughness value of 0.487 µm. The findings confirm that a lower feed rate setting is essential achieving high-quality surface finishes in SS400 steel machining.

Keyword : CNC lathe, surface quality, spindle speed, feed rate, taguchi method

Abstrak

Proses pemesinan bubut CNC merupakan salah satu teknologi utama dalam industri manufaktur modern karena mampu menghasilkan komponen dengan presisi tinggi dan waktu produksi yang efisien. Mesin bubut CNC digunakan untuk membentuk permukaan luar maupun dalam benda kerja melalui perputaran material yang kemudian dipertemukan dengan pahat potong. Salah satu faktor krusial dalam proses ini adalah pengaturan parameter pemesinan, seperti kecepatan putaran spindel dan laju umpan, yang berpengaruh langsung terhadap kualitas permukaan hasil pemotongan. Namun, hingga kini masih ditemukan ketidakseragaman hasil penelitian sebelumnya terkait parameter optimal untuk memperoleh kekasaran permukaan terbaik pada material baja SS400 yang banyak digunakan di industri konstruksi dan otomotif. Kondisi ini menunjukkan adanya gap penelitian, di mana diperlukan kajian eksperimental yang lebih spesifik terhadap karakteristik material SS400 dengan metode pengujian yang terukur. Penelitian ini bertujuan untuk menganalisis pengaruh variasi kecepatan spindel dan laju umpan terhadap kualitas permukaan baja SS400 pada proses pemesinan bubut CNC dengan menggunakan metode Taguchi. Proses eksperimen dilakukan pada mesin CNC Liouy Hsing 450 dengan pahat potong tipe WNMG sebagai variabel tetap, serta variasi kecepatan spindel 800, 1000, dan 1200 putaran per menit dan laju umpan 0,1; 0,2; dan 0,3 mm per menit. Pengumpulan data dilakukan melalui observasi dan dokumentasi, kemudian hasilnya diolah menggunakan perangkat lunak Microsoft Excel untuk memperoleh nilai kekasaran rata-rata permukaan. Hasil penelitian menunjukkan bahwa laju umpan memiliki pengaruh yang lebih signifikan dibandingkan kecepatan spindel terhadap kekasaran permukaan. Kondisi optimum diperoleh pada kombinasi kecepatan spindel 1000 putaran per menit dan laju umpan 0,1 mm per menit dengan nilai kekasaran permukaan paling halus sebesar 0,487 µm.

Penelitian ini menegaskan pentingnya pengaturan laju umpan rendah untuk mencapai hasil pemesinan berkualitas tinggi pada baja SS400.

Kata kunci: bubut CNC, kualitas permukaan, kecepatan spindel, laju umpan, metode Taguchi

1. Introduction

The development of modern manufacturing technology demands continuous improvement in efficiency and precision throughout every stage of the production process. One of the most widely adopted technologies in the manufacturing industry is the CNC (Computer Numerical Control) lathe machine, which enables material cutting processes to be performed automatically and accurately. The machine operates on the principle of rotating the workpiece and bringing it into contact with a cutting tool, allowing the formation of both external and internal surfaces of the material according to the desired design [1]. The CNC turning process is commonly used to produce cylindrical and flat components with high dimensional accuracy. Its main advantage lies in the precise control of machining parameters such as spindle speed, feed rate, and depth of cut, which can be adjusted according to specific requirements. These parameters directly influence the surface quality of the machined product, which serves as one of the key indicators of production success [2].

One of the most frequently used materials in machining processes is SS400 steel — a type of hot-rolled steel characterized by good tensile strength, as well as excellent formability and weldability [3]. This material is widely applied in the automotive, construction, and machine component industries due to its balance between mechanical strength and machinability [4]. However, SS400 also exhibits surface variation depending on the accuracy of cutting parameter settings during machining. The surface quality of machined SS400 steel is highly affected by the combination of spindle speed and feed rate. A common issue encountered in industrial practice is the absence of standardized parameter values that can be universally applied to achieve optimal surface roughness on this material. Differences in machine type, cutting tools, and machining conditions often result in inconsistent surface outcomes across production processes. Therefore, an experimental study is required to determine the most effective parameter combination for achieving minimal surface roughness.

Furthermore, while some previous studies have identified spindle speed as the dominant factor influencing the final surface quality, more recent findings indicate that feed rate may exert a stronger effect on surface roughness variations [4][5]. This inconsistency in empirical results highlights the need for further systematic investigation using an optimized and quantifiable approach.

Kurniawan et al. [1] designed a two-axis mini-CNC lathe and emphasized the importance of controlling cutting parameters to achieve both geometric accuracy and superior surface finish. Meanwhile, Febrianton and Putri [4] found that an increase in spindle speed is directly proportional to the enhancement of surface hardness in carbon steel; however, its effect on surface roughness does not always follow a linear trend. Suker et al. [5] conducted a comparative study on various materials in the turning process and concluded that feed rate has the most significant influence on surface roughness compared to other parameters, particularly in materials with dense crystalline structures such as carbon steel. Additionally, a technical study by Mitutoyo [6] explained that surface roughness can be quantitatively classified based on the Ra (average roughness) value, where a smaller Ra indicates a smoother surface quality.

In the context of parameter optimization, Jung and Lee [7] demonstrated the effectiveness of the Taguchi method in determining optimal parameter combinations for complex engineering processes. Although their research was conducted on a Proton Exchange Membrane Fuel Cell (PEMFC) system, the principle of applying the Taguchi method to identify dominant factors and optimal combinations is highly relevant to CNC machining processes. Therefore, implementing this method is expected to yield more efficient and measurable results in machining SS400 steel. Based on the literature review, most previous studies have focused on the relationship between spindle speed and either surface hardness or cutting force, rather than specifically examining the interaction between spindle speed and feed rate in determining the surface roughness of SS400 steel. Moreover, the application of the Taguchi method to SS400 material remains limited, particularly in experimental setups that replicate real industrial machining conditions. Hence, there exists a research gap that must be addressed to gain a more comprehensive understanding of the influence of machining parameters on the surface quality of SS400 steel.

This study aims to experimentally analyze the effect of spindle speed and feed rate variations on the surface quality of SS400 steel during CNC turning and to determine the parameter combination that produces the lowest surface roughness using the Taguchi method. The results of this study are expected to provide practical insights for determining optimal machining parameters in manufacturing industries that utilize SS400 steel as a primary material.

2. Method

Research Variable

Two types of variables can be used to collect experimental data: independent variables and response variables. Independent variables are variables that have a value and can be monitored and determined according to research considerations. To achieve the research objectives, three components will be used as independent variables in this study. Table 1 shows how each element is divided into three levels.

Table 1. Variable factor

Parameters	Level 1			Level 2			Level 3		
Spindle Speed (rev/min)	800			1000			1200		
Feed Rate (mm/min)	0.1	0.2	0.3	0.1	0.2	0.3	0.1	0.2	0.3

Variables whose values cannot be changed or predicted initially and are affected by the treatment received are known as response variables. The value of this variable can be known after the experiment is completed. In this study, surface roughness will be used as the response variable.

Material

With its excellent strength-to-weight ratio, excellent flexibility, and exceptional corrosion resistance, SS400 (Structural Steel 400) is an excellent choice for structural steel. Due to its unique properties, this material is widely used in a variety of applications and industries, especially in construction, automotive, and shipbuilding [3]. The composition of a material determines its strength, toughness, and resistance to corrosion.

This material is solid because of its low carbon content. It is not recommended for hard, wear-resistant, or strong main parts. On the contrary, this steel is very suitable for machining and welding. Usually used for welding small nuts, structural parts, car and motorcycle parts, and other parts [4].

Problem Identification

The resulting surface roughness or smoothness is a way to determine a quality product. Surface roughness is the main factor in determining whether a machined product is acceptable or not. Surface roughness is a very important mechanical property because it can be used to determine other mechanical properties such as strength, ductility, and hardness.

Lathe conditions, cutting speed, depth of cut, machine conditions, workpiece material, tool type, tool sharpness, cutting geometry or angle, cooling, and operator are some of the factors that affect the surface roughness [5].

Roughness Parameters

Surface roughness rises if these parameters are not conveniently selected. Cracks, reduced fatigue strength, and corrosion resistance are the results of this condition, which also produces notching effects. Therefore, measuring and characterizing surface roughness is essential for optimizing machining processes.

The average roughness of the profile with respect to the mean line (often the least squares mean line or the one produced by a standard filter) is known as average roughness (Ra). Possibly the most popular "quoted" metric, it shows the average absolute departure of the profile points from a mean line [6]. The roughness parameters are explained in the EN ISO 4287:1997 standard. Some common parameters are:

1. Ra – arithmetical mean roughness value: The arithmetical mean of the absolute values of the profile deviations (Zi) from the mean line of the roughness profile, shown in Figure 1.

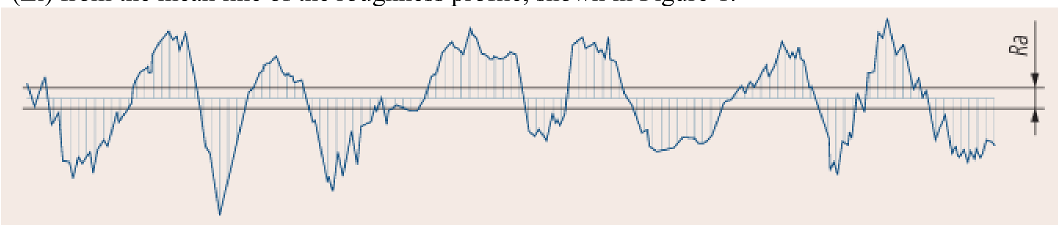

Figure 1. Arithmetical mean roughness value Ra [7]

2. Rt – total height of the roughness profile: Difference between height Zp of the highest peak and depth Zv of the deepest valley within the evaluation length, shown in Figure 2.

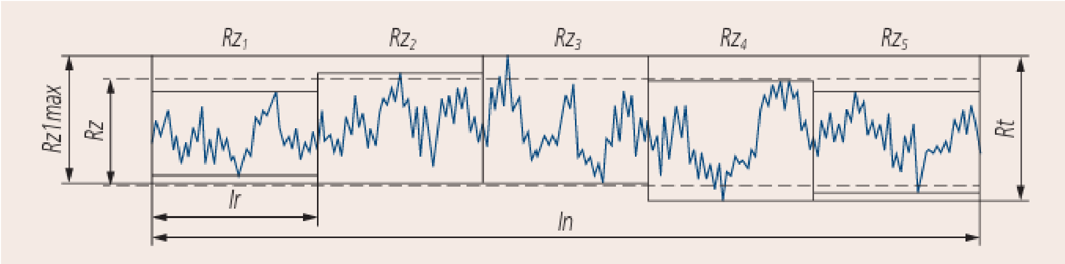

Figure 2. Total height of the roughness profile Rt, mean roughness depth Rz, and maximum roughness depth Rz1max [7]

3. Rz – mean roughness depth: Mean value of the five Rzi values from the five sampling lengths Iri within the evaluation length In.
4. Rzi – greatest height of the roughness profile: Sum of the height of the highest profile peak and the depth of the deepest profile valley, relative to the mean line, within a sampling length Iri.
5. Rz1max – maximum roughness depth: Largest of the five Rzi values from the five sampling lengths Iri within the evaluation length In.

ISO/R 468-1966 provides provisions and numerical values for three types of surface roughness. ISO has divided the arithmetic mean roughness values into twelve levels, ranging from N1 to N12.

Table 2. Classification of roughness values and their symbols

Roughness value (Ra in µm)	**Roughness grade number**	**Roughness grade symbol**
50	N12	
25	N11	∇
12.5	N10	
6.3	N9	
3.2	N8	∇∇
1.6	N7	
0.8	N6	
0.4	N5	∇∇∇
0.2	N4	
0.1	N3	∇∇∇∇
0.05	N2	
0.025	N1	

Taguchi Method

In the optimization process, Dr. Genichi Taguchi introduced the Taguchi method, which is a statistical technique used for experimental optimization. This method usually involves analyzing the sensitivity of each factor to the response to determine the optimal combination of factors [16]. Using the Orthogonal Arrays method, the experiment was conducted by combining the spindle speed and feed rate from Table 1. and substituting them with Table 3. Each parameter will have two levels, with P (Parameter) = 2 and L (Level) = 3. This study will use the L9(9) orthogonal array.

Table 3. L9(9) Orthogonal Arrays

Experiment Number	**A**	**B**	**X**
1	1	1	X1
2	1	2	X2
3	1	3	X3
4	2	1	X4
5	2	2	X5
6	2	3	X6
7	3	1	X7
8	3	2	X8
9	3	3	X9

The result of the substitution and the added experimental variable are shown in Table 4.

Table 4. Taguchi orthogonal arrays

Experiment Number	**Spindle Speed** (rev/min)	**Feed Rate** (mm/min)	**X**
1	800	0.1	X1
2	800	0.2	X2
3	800	0.3	X3
4	1000	0.1	X4
5	1000	0.2	X5
6	1000	0.3	X6
7	1200	0.1	X7
8	1200	0.2	X8
9	1200	0.3	X9

3. Result and Discussion

Experiment Data

The material goes through a turning process, which produces 9 specimens, then is measured using a surface roughness measuring tool that obtains experimental results. As shown in Table 5 .

Table 5. Experimental Result Data

Experiment Number	**Spindle Speed** (rev/min)	**Feed Rate** (mm/min)	**Surface Roughness** (µm)
1	800	0.1	1.116
2	800	0.2	1.597
3	800	0.3	2.097
4	1000	0.1	0.487
5	1000	0.2	1.122
6	1000	0.3	2.087
7	1200	0.1	0.683
8	1200	0.2	1.333
9	1200	0.3	2.234

Figure 3 shows the cutting results after the machining process and the roughness results with the highest and lowest values.

Figure 3. Cutting and Roughness test result: (a) Experiment 4, roughness 0.487 µm and (b) Experiment 9, roughness 2.234 µm

S/N Ratio

After getting the Ra results from each experiment, to see the most optimal combination, the Ra value is substituted into the S/N Ratio formula, the smaller the better, so that the value is obtained as in Table 6.

Table 6. S/N ratio value for Ra

Experiment Number	Ra (μm)	S/N Ratio
1	1.116	-0.953
2	1.597	-4.066
3	2.097	-6.432
4	0.487	6.249
5	1.122	-1.000
6	2.087	-6.390
7	0.683	3.312
8	1.333	-2.497
9	2.234	-6.982

A table called the S/N Ratio response table is used to analyze the effect of spindle speed and feed rate on surface roughness. The S/N ratio response table is shown in Table 7.

Table 7. S/N ratio response table for Ra

Factors	Level 1	Level 2	Level 3	Delta	Rank
Spindle Speed	-3.817	**-0.380**	-2.056	3.437	2
Feed Rate	**2.869**	-2.521	-6.601	9.471	1

When Table 7 is examined, it is determined that the most effective parameter is the feed rate. It is also found that changes in spindle speed have a significant effect on Ra. Table 7 can also be depicted as shown in Figure 4.

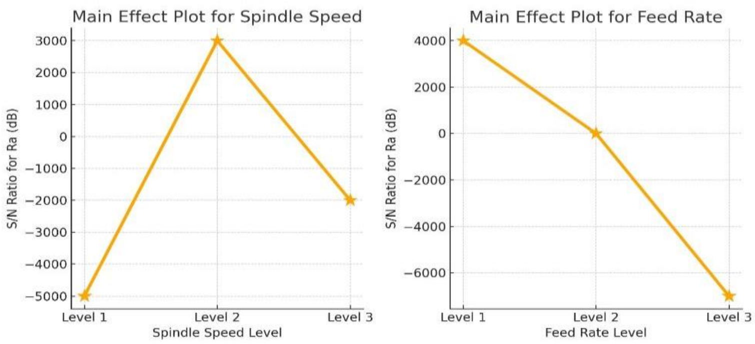

Figure 4. Main effect plot for S/N ratio for Ra

As shown in Figure 4, the optimal cutting conditions are a spindle speed of 1000 rev/min and a feed rate of 0.1 mm/rev because the smallest S/N ratio gives the best results.

Time Difference

The machining process also affects the time spent, in this case, good results with less processing time will be an added value. Table 8 will show the time produced in each experiment.

Table 8. Time spent on each experiment

Experimental Number	Time Spent (In one cycle)
1	3' 17"
2	3' 4"
3	3' 0"
4	3' 10"
5	3' 0"
6	2' 57"
7	3' 5"
8	2' 57"
9	2' 54"

As seen in Table 8, although experiment number 4 has the best roughness results, its machining time is not the best. On the contrary, experiment number 9 has the worst hardness results but has the shortest machining process than the others. If we look at the time difference of each experiment, there are not many significant changes. Changes in spindle speed have a time difference range of 3-13 seconds, while changes in feed rate have a time difference range of 3-7 seconds. This shows that spindle speed has a higher influence than feed rate because it has the largest time difference.

Correlation Between Roughness and Time

After seeing which variables have the most influence on each category, to see more clearly the influence, by combining the results of surface roughness and also the time spent in one cycle. Figure 5 will show a graph that combines both data.

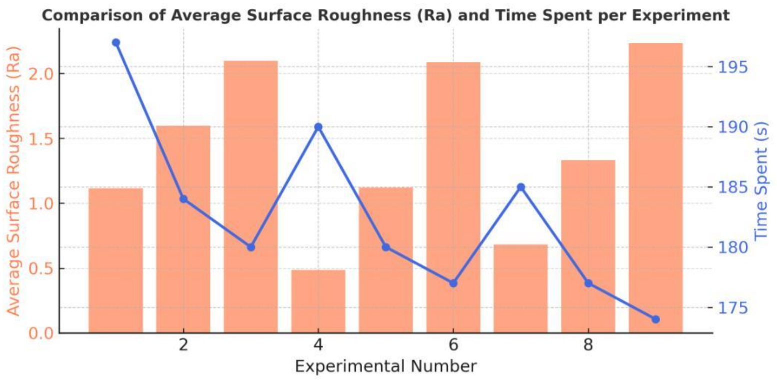

Figure 5. Combination of two data

What is shown in the graph above is that the variables make different results. In the roughness test, each variable has the same trend, following the influence of changes in each variable. Then in the test of the time spent in one cycle tends to have a positive trend where the time required decreases relatively as the spindle speed and feed rate variables change.

Looking back at the graph, the correlation between the two tests is: If you want to get good surface roughness results, it takes longer in one cutting cycle. Vice versa, if the time required is faster, the cutting results on the roughness surface are bad.

4. Conclusion

From this research, we have a conclusion:

1. Effect of Feed Rate on Surface Roughness: The experimental results clearly show that as the feed rate increases, the surface roughness (Ra) value also increases, indicating poorer surface quality. Specifically, when the feed rate was set at 0.1 mm/rev, the average roughness achieved was 0.487 µm, while at 0.3 mm/rev, the roughness rose significantly to 2.234 µm. This finding confirms that feed rate is a critical parameter influencing the finish quality, and even small increments can drastically change the micro-texture of the surface.
2. Effect of Spindle Speed on Surface Roughness: Conversely, the results show that higher spindle speeds tend to produce smoother surfaces. At 800 rpm, the average Ra value was around 1.6 µm, while at 1200 rpm, the surface roughness decreased to below 0.7 µm. The optimal combination was obtained at spindle speed = 1000 rpm and feed rate = 0.1 mm/rev, corresponding to Experiment 4, which achieved the lowest roughness value of 0.487 µm.
3. Comparison with Standard Surface Finish Grades: According to the general ISO 1302 surface roughness classification, a surface with Ra between 0.4–0.8 µm is categorized as fine machining (Grade N6–N7), typically achievable through precision turning or fine grinding. Therefore, the best result from this experiment (Ra = 0.487 µm) is within the acceptable range of precision machining standards, indicating that the selected parameters are suitable for industrial applications requiring fine finishes.
4. Time Performance Analysis: The difference in machining time across all experiments is relatively small, ranging between 174–197 seconds. Changes in spindle speed caused variations of approximately 3–13 seconds, while changes in feed rate affected the time by 3–7 seconds. This indicates that spindle speed has a greater influence on machining time compared to feed rate. Despite this, the time variations are still within efficient machining limits, suggesting that optimizing surface finish does not significantly compromise production time.
5. Correlation Between Surface Roughness and Time: The analysis of the combined plot (Figure 5) reveals an inverse correlation between surface roughness and machining time. When the surface roughness value decreases

(indicating smoother surfaces), the machining time tends to increase slightly, and vice versa. This behaviour aligns with machining theory, where slower feed and higher spindle speeds lead to better surface finish but require longer cycle times

Recommendation

From this research, the author recommends for further research:

1. Entering other variables as research materials, such as coolant conditions, cutting tool variations, and also cutting depth.
2. Varying the cutting, such as level cutting, will create many test points which will be directly proportional to more accurate test results.
3. With the poor correlation between the surface roughness results and the time spent on this study, the next researcher is to look for ideal results where the time spent remains short but has satisfactory results.
4. Conducting research with the main goal of getting the fastest and optimal cutting results.

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