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Analysis of Spindle Speed Influence on Surface Roughness and HSS-Co Tool Vibration in The Turning of ST 41 Steel Using the *Taguchi Method*

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Abstract

Surface roughness and tool vibration are critical parameters in evaluating machining quality and process stability. This study aims to analyze the effect of spindle speed on surface roughness and tool vibration during the turning of ST 41 steel using an HSS-Co cutting tool (5% cobalt). The Taguchi method with an L8 orthogonal array was employed for experimental design and Signal-to-Noise (S/N) ratio analysis, while Analysis of Variance (ANOVA) was used to identify the most influential factor. Experiments were conducted on a conventional lathe with spindle speeds ranging from 100 to 700 rpm and a constant depth of cut of 0.5 mm. The results indicate that increasing spindle speed significantly reduces surface roughness, but simultaneously increases tool vibration. The lowest surface roughness (9.31–9.32 μm) was achieved at 700 rpm with a vibration velocity of 19.43 mm/s, whereas the highest roughness (21.62 μm) occurred at 100 rpm with a lower vibration velocity of 5.81 mm/s. These findings reveal a trade-off relationship between surface quality and vibration stability. S/N ratio analysis and ANOVA confirm that spindle speed is the dominant factor affecting both surface roughness and tool vibration. Therefore, optimizing spindle speed is essential to achieve improved surface quality while maintaining acceptable vibration levels in conventional turning processes.

1. Introduction

The turning process is one of the most common machining methods in the manufacturing industry, especially to produce cylindrical components with precise dimensional tolerances and good surface quality. Parameters in the turning process include spindle speed (rotation of the main shaft of the lathe), feed rate, depth of cut, as well as cutting conditions such as tool vibration and system rigidity. For medium steel materials such as ST 41 Steel, which is widely used in construction and machine components, surface quality and cutting stability are critical factors. Tools with HSS-Co (High Speed Steel with cobalt addition) material are widely chosen because of their combination of hardness and relatively good heat resistance for machining medium steel. Supporting theory may also be included in this section. In two aspects it is often noted the surface roughness value (Ra or Rz) which indicates how fine the machining results are, and, the speed or amplitude of the vibration of the tool during the cutting process, which can affect the surface yield and wear of the tool [1].

Vibration of the tool due to deflection, chatter, or cutting instability can degrade the quality of the work, accelerate the damage of the chisel, and increase production costs [2].

Previous research has been conducted by [3], showing that spindle speed plays an important role in surface quality and cutting conditions. The turning process of aluminum alloy 6063, using the Taguchi method (orthogonal array L9) showed a contribution of spindle speed of ±59.71% to the roughness of the surface [4]. In aluminum 6061 shows that the spindle speed has a contribution of about 51.80% to the surface roughness [5]. Taguchi's method also shows that spindle speed is a significant variable in surface roughness optimization. [6].

In addition, research on machine/chisel vibration and its relationship with surface quality has also been conducted. Research on milling cuts on aluminum using carbide chisels shows that radial vibration is strongly influenced by spindle speed [7], and surface roughness values are also strongly influenced by spindle speed [8]. [9] Conducting a study of AISI 1045 steel turning using the Taguchi method showed that spindle speed and feed rate affect both surface roughness and vibration amplitude. Research on the relationship of HSS-Co tool conditions in the context of drilling/geopolymer showed that HSS-Co chisels produced better surface roughness values than regular HSS and HSS-TiN at certain spindle speeds. [10].

The Taguchi method has been widely recognized as an efficient experimental design technique for optimizing manufacturing processes. It employs orthogonal arrays to minimize the number of experimental runs, while utilizing Signal-to-Noise (S/N) ratios and Analysis of Variance (ANOVA) to identify the most influential factors [11]. Recent studies have demonstrated that the Taguchi method is effective in determining optimal machining parameters in various processes, including turning, drilling, and milling, as well as in quantifying the contribution of each parameter to output quality [12]. Furthermore, recent research indicates that spindle speed is a dominant parameter affecting both surface roughness and tool vibration in machining operations [13], [14], [15].

However, most previous studies have examined surface roughness and tool vibration separately and have predominantly focused on carbide cutting tools. Studies that simultaneously investigate both responses, particularly in the turning of low-carbon steel such as ST 41 using HSS-Co cutting tools, remain limited. In addition, the exploration of a wide range of spindle speeds in conventional turning machines has not been extensively reported in recent literature.

Based on these gaps, this study aims to provide a comprehensive understanding of the effect of spindle speed variation on surface roughness and tool vibration during the turning of ST 41 steel using an HSS-Co cutting tool. This research measures and analyzes the influence of spindle speed on surface roughness and vibration velocity, and applies the Taguchi method to design the experiments and determine the optimal parameter settings. The novelty of this study lies in its integrated approach to evaluating the trade-off between surface finish quality and dynamic stability, offering a data-driven model to synchronize conflicting variables for superior manufacturing performance.

2. Research Methodology

2. 1. Method

This research began with a literature study to collect theories and previous research results relevant to the turning process, surface roughness, chisel vibration, and the application of the Taguchi method. Experiments were carried out with spindle speed variations of 100, 200, 300, 400, 500, 600, and 700 rpm with a fixed cutting depth of 0.5 mm. After the turning process, surface roughness testing is carried out using a surface roughness tester and tool vibration speed testing using a vibrometer. The test results were then analyzed using the Taguchi method through the calculation of Signal-to-Noise (S/N) Ratio and Variance Analysis (ANOVA) to determine the optimal combination of parameters and the most influential factors [16].

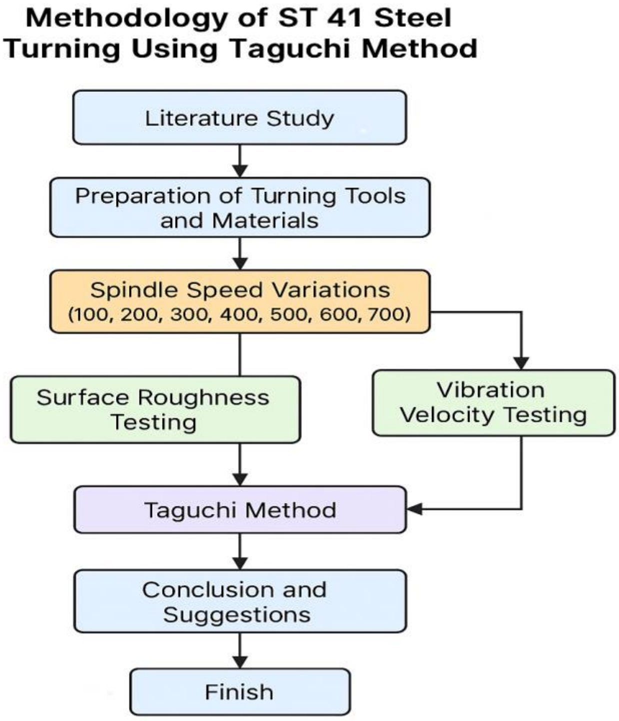

FIGURE 1. Simulation result

2. 2. Materials and Tool

FIGURE 2. Conventional Lathe

The conventional lathe used is type CQ6230A×910, which plays the main role in this study. This lathe is used to carry out the turning process on ST 41 steel material, with the aim of analyzing the effect of variations in spindle rotation speed on surface roughness and vibration speed of HSS-Co chisels.

The use of CQ6230A×910 type lathes was chosen because it has the ability to precisely set cutting parameters, as well as being able to produce stable and controlled turning results [17]. This machine allows accurate measurements of the surface roughness value (Ra) and vibration speed of the tool during the machining process. Thus, conventional lathes serve as the main means of obtaining the experimental data needed for analysis using the Taguchi method, so that optimal spindle speed parameters can be identified that produce the best surface quality.

FIGURE 3. HSS Cutting Tool (Co 5%)

The HSS (Co 5%) cutting tool used in this study is made of High Speed Steel (HSS) alloyed with 5% cobalt. The addition of cobalt enhances hot hardness, wear resistance, and the ability to maintain cutting edge sharpness at elevated temperatures. This type of tool was selected due to its stable cutting performance when machining medium carbon steel such as ST 41, and its suitability for use in conventional lathe operations without requiring intensive cooling systems. Furthermore, the selection of HSS-Co tools is based on practical and economic considerations. These tools are still widely used in small- to medium-scale industries due to their relatively lower cost compared to carbide tools, as well as their ease of re-sharpening. With these characteristics, HSS-Co tools are considered representative for evaluating the influence of machining parameters, particularly spindle speed, on surface roughness and tool vibration under conventional machining conditions.

FIGURE 4. (A) Vibration meter ,(b) Surface Roughness Tester.

The Surface Roughness Tester and Vibration Meter are the two main measuring instruments used in this study to analyze the results of the ST 41 steel turning process using a 5% HSS-Co chisel. Both of these tools function in the collection of quantitative data that is the basis of analysis in the Taguchi method.

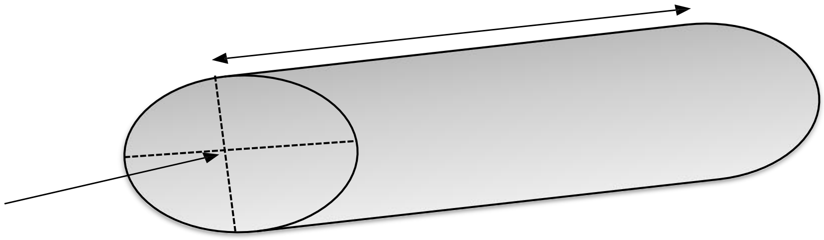

FIGURE 5. ST 41 steel

The selection of ST 41 steel in this study was based on the consideration that this material is often used in the construction of engines, shafts, frames, and other mechanical components, so that the results of the study can provide practical implications for improving surface quality and machining stability in materials commonly applied in industry. and support the application of the Taguchi method in determining optimal machining conditions in conventional turning processes.

2. 3. Research Procedure

The study began with the preparation of equipment and materials, including a conventional lathe (CQ6230A×910), an HSS Co 5% cutting tool (3/8"×4"), a caliper, a vibration meter, a surface roughness tester, a grinding machine, personal protective equipment (gloves and safety glasses), and ST 41 steel as the workpiece material. The lathe was then set with spindle speed variations of 100, 200, 300, 400, 500, 600, and 700 rpm, a constant depth of cut of 0.5 mm, and a uniform feed rate for all experimental runs. Tool vibration measurements were conducted using a vibration meter. Prior to data acquisition, the instrument was calibrated according to the manufacturer’s procedure using its internal calibration function to ensure measurement accuracy. The calibration process involved verifying the instrument response against a standard reference signal at a specified frequency and amplitude, ensuring that any deviation remained within acceptable limits. After calibration, the sensor was mounted consistently on the tool holder or near the cutting zone with the same orientation for all tests to minimize measurement variability. Vibration data were recorded under steady-state cutting conditions and expressed in mm/s for each spindle speed variation. Surface roughness measurements were performed using a surface roughness tester. The device was calibrated prior to measurement using a standard reference specimen with a known roughness value (Ra) to ensure accuracy and repeatability. The calibration included stylus adjustment and verification of readings within the permissible tolerance range. A total of 21 ST 41 specimens were cleaned to remove debris and oil, and five measurement points were defined on each machined surface. Measurements were carried out on a flat surface with the tracing direction parallel to the feed direction. The surface roughness (Ra) values were recorded at each point and averaged for further analysis. All experimental data were subsequently analyzed using the Taguchi method to determine the optimal machining parameter combination.

3. Results and Discussion

3.1 Roughness Test Results

TABLE 1. Data from the research on roughness value in ST 41 Steel

No	Rotation speed (rpm)	Specimen	Degree of roughness (µm)					Ra Average (µm)	Ra Total (µm)
			Ra_1	Ra_2	Ra_3	Ra_4	Ra_5		
1	100	1	21.22	21.16	21.17	21.12	21.22	21.178	21.62
		2	22.22	22.19	22.05	22.21	22.07	22.148	
		3	21.65	21.57	21.52	21.49	21.48	21.542	
2	200	1	19.47	19.28	19.57	19.48	19.46	19.452	19.15
		2	18.9	18.88	18.87	18.77	18.76	18.836	
		3	19.21	19.18	19.11	19.18	19.21	19.178	
3	300	1	17.15	17.16	17.16	17.14	17.13	17.148	16.89
		2	16.89	16.89	16.87	16.82	16.82	16.858	
		3	16.72	16.69	16.65	16.65	16.63	16.668	
4	400	1	15.12	15.10	15.13	15.13	15.14	15.124	14.96
		2	15.15	15.14	15.13	15.13	15.11	15.132	
		3	14.80	14.70	14.65	14.60	14.50	14.65	
5	500	1	13.70	13.70	13.63	13.58	13.55	13.632	13.28
		2	13.55	13.50	13.48	13.40	13.37	13.46	
		3	12.85	12.85	12.78	12.70	12.69	12.774	
6	600	1	11.75	11.75	11.67	11.56	11.56	11.658	11.29
		2	11.50	11.48	11.42	11.38	11.38	11.432	
		3	10.90	10.80	10.80	10.76	10.68	10.788	
7	700	1	9.90	9.89	9.70	9.68	9.65	9.764	9.31
		2	9.75	9.75	9.65	9.65	9.40	9.64	
		3	8.70	8.70	8.45	8.40	8.38	8.526	

In figure 6, it can be seen that the effect of rotational speed on roughness in ST 41 steel in the turning process with variations in rotational speed of 100 rpm, 200 rpm, 300 rpm, 400 rpm, 500 rpm, 600 rpm, and 700 rpm. At a rotational speed of 100 rpm the total roughness value is 21.62 µm, at a rotational speed of 200 rpm the total roughness value is 19.15 µm, at a rotational speed of 300 rpm the total roughness value is 16.89µm, at a rotational speed of 400 rpm the total roughness value is 14.96 µm, at a rotational speed of 500 rpm the total roughness value is 13.28 µm, At a rotational speed of 600 rpm the total roughness value is 11.29 µm, and at a rotational speed of 700 rpm the total roughness value is 9.31 µm.

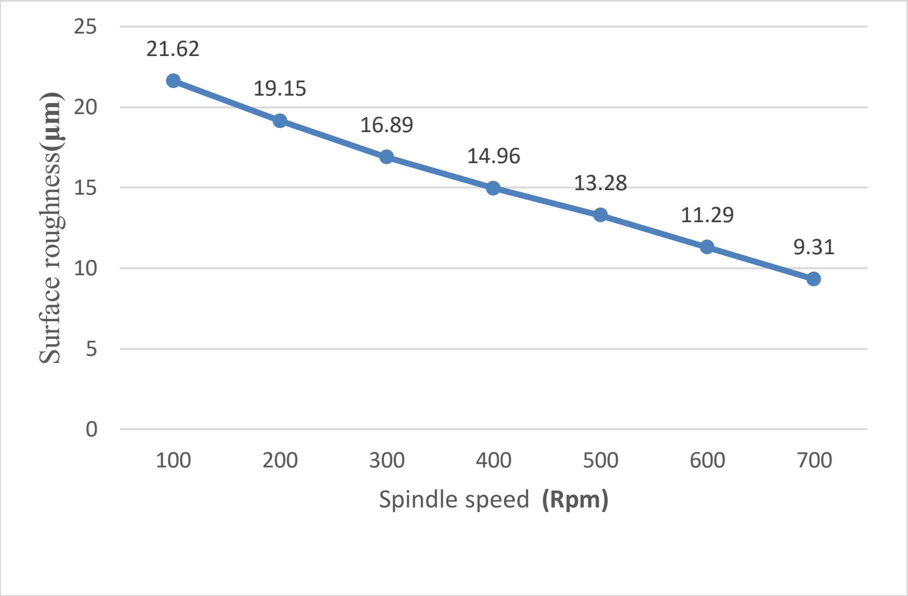

FIGURE 6. Graph of rotational speed against surface roughness in ST 41 steel

From the graph, it can be seen that the turning process that produces good roughness (the lowest) is the turning process with a spindle rotation speed of 700 Rpm with a cutting depth of 0.5 mm, which is 9.31 µm, while for the turning process that produces the highest roughness (the highest) is the turning process with a spindle rotation speed of 100 rpm with a cutting depth of 0.5 mm, which is 21.62 µm, meaning the higher the spindle speed, then the surface roughness value on ST 41 steel is lower and the lower the speed on the spindle, the surface roughness value on the spindle ST 41 steel is getting high. Research results trends show that an increase in spindle speed from 100 rpm to 700 rpm causes a significant decrease in surface roughness. This indicates that at higher speeds, the cutting process becomes more stable, chip formation is more continuous, and the tendency for built-up edge (BUE) formation decreases, resulting in a smoother surface.

3.2. Vibration Speed Results

TABLE 2. Data from vibration speed research on HSS-Co chisels.

No	Rotation speed (rpm)	Specimen	Vibration Speed (mm/s)					Vibration Speed Average (mm/s)	Total Vibration Speed (mm/s)
			n1	n2	n3	n4	n5		
1	100	1	5.7	4.7	4.7	3.7	4.7	4.7	5.81
		2	6.2	6.1	6	6	5.8	6.02	
		3	6.8	6.7	6.8	6.7	6.6	6.72	
2	200	1	9.8	9.8	9.7	9.7	9.6	9.72	9.72
		2	10	9.7	9.7	9.6	9.6	9.72	
		3	9.9	9.8	9.7	9.7	9.6	9.74	
3	300	1	13.6	13.55	13.52	13.48	13.51	13.532	13.37
		2	13.2	13.28	13.24	13.22	13.22	13.232	
		3	13.3	13.4	13.39	13.37	13.35	13.35	
4	400	1	14.80	14.81	14.65	14.32	14.41	14.598	14.53
		2	14.15	14.14	14.14	14.12	14.13	14.136	
		3	15.80	14.88	14.78	14.55	14.30	14.862	
5	500	1	16.50	16.30	16.15	16.15	16.10	16.24	16.49
		2	16.80	16.79	16.50	16.50	16.30	16.578	
		3	16.90	16.86	16.70	16.40	16.40	16.652	
6	600	1	17.60	17.60	17.55	17.46	17.46	17.534	17.82
		2	17.55	17.50	17.43	17.40	17.40	17.456	
		3	18.96	18.96	18.75	17.90	17.89	18.492	
7	700	1	19.73	19.67	19.67	19.59	19.45	19.622	19.43
		2	19.54	19.54	19.30	19.32	18.98	19.336	
		3	19.44	19.44	19.28	19.30	19.20	19.332	

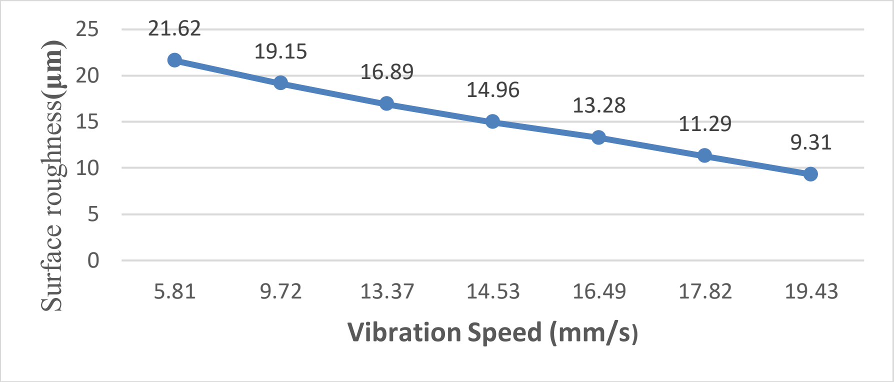

FIGURE 7. Graph of Speed Vibration against surface roughness in ST 41 steel

In the graphic figure 7, it can be seen that the effect of vibration speed on roughness in ST 41 steel in conventional turning processes. At a vibration speed of 5.81 mm/s it produces a total roughness value of 21.62 µm, at a vibration speed of 9.72 mm/s a total roughness value of 19.15 µm, at a vibration speed of 13.37 mm/s a total roughness value of 16.89 µm, at a vibration speed of 14.53 mm/s a total roughness value of 14.96 µm, and at a vibration speed of 16.49 mm/s with a total roughness value of 13.28 µm, At a vibration speed of 17.82 mm/s the total roughness value is 11.29 µm, and at a vibration speed of 19.43 mm/s the total roughness value is 9.31 µm. From the graph, it can be seen that the vibration speed that produces good roughness (the lowest) is the vibration speed of 19.43 mm/s, the total roughness value is 9.31 µm, while for the vibration speed that produces the highest roughness (highest) is the vibration speed process of 5.81 mm/s resulting in a total roughness value of 21.62 µm, meaning that the higher the vibration speed, then the lower the surface roughness value in ST 41 steel and the lower the vibration velocity, the higher the surface roughness value in ST 41 steel.

The vibration speed shows an increasing trend along with the rise in spindle speed. This increase is caused by the additional frequency of dynamic excitation during the cutting process. However, even though the vibration values increase, the surface quality continues to improve. This indicates that the occurring vibrations are still in a stable condition (forced vibration) and have not developed into chatter that could damage the machined surface. Thus, there is a nonlinear relationship between surface roughness and vibration, where an increase in vibration does not always negatively impact surface quality.

3.3. Analysis of the Spindle Speed Taguchi Method on Roughness.

TABLE 3. Orthogonal Array Roughness Testing

Parameter 1	Parameter 2
1	1
1	2
2	1
2	2
3	1
3	2
4	1
4	2

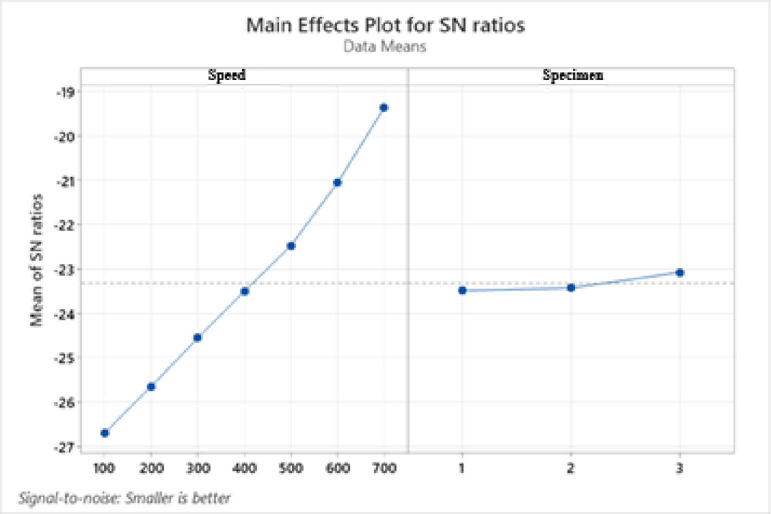

FIGURE 8. Main Effects for SN ratios

TABLE 4. Response Table for Signal to Noise Ratios

Level	**Speed**	**Specimen**
1	-26.70	-28.79
2	-25.65	-24.13
3	-24.55	-21.53
4	-23.50	
5	-22.47	
6	-21.05	
7	-19.36	
Delta	7.33	0.42
Rank	1	2

3.4. Analysis of the Taguchi method of spindle Speed against vibration.

TABLE 5. Orthogonal Array Vibration Testing

Parameter 1	Parameter 2
1	1
1	2
2	1
2	2
3	1
3	2
4	1
4	2

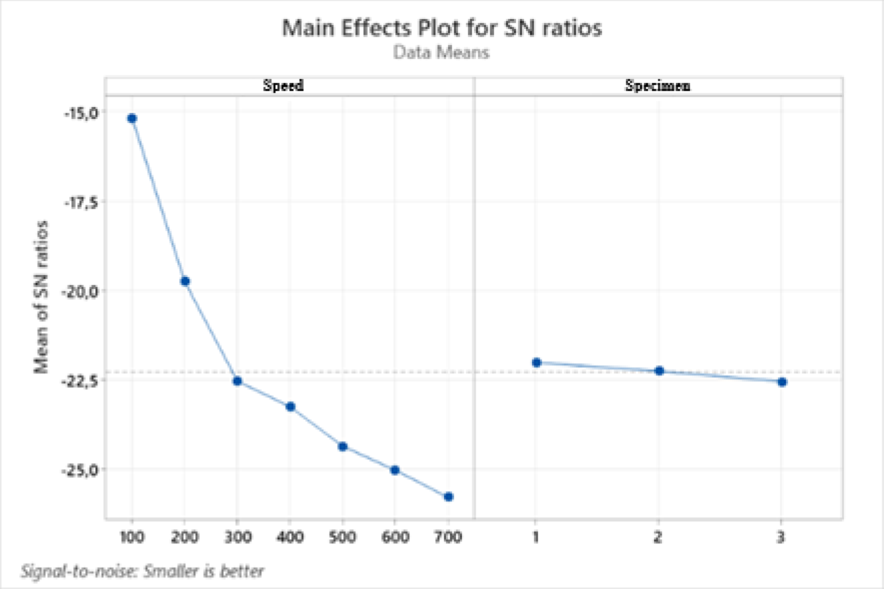

FIGURE 9. Main Effects for SN ratios

TABLE 6. Response Table for Signal to Noise Ratios Vibration

Level	Speed	Specimen
1	-15.19	-22.01
2	-19.76	-22.25
3	-22.52	-22.54
4	-23.24	
5	-24.34	
6	-25.02	
7	-25.77	
Delta	10.58	0.53
Rank	1	2

The Taguchi method was used in this study to optimize the spindle rotation speed in order to obtain the best results on the surface roughness and vibration of the HSS-Co chisel during the ST 41 steel turning process. The Orthogonal Array (OA) design is used to efficiently analyze various speed variations. The analysis was performed with Signal-to-Noise Ratio (S/N Ratio) to determine the optimal conditions that resulted in the most stable machining results [18]. Analysis of Variance (ANOVA) to assess the significant influence of each factor on turning results [19].

This study shows that spindle speed has a very decisive influence on the quality of turning results. In the surface roughness test, Taguchi's analysis with OA L8 showed that an increase in spindle speed from 100 to 700 rpm resulted in a significant decrease in the value of the S/N ratio in the *characteristics of smaller is better*, which means that the surface roughness is smaller. This is supported by the largest Delta value in the speed parameter, so that spindle speed is the main factor controlling surface quality, while the influence of specimen type is relatively small." On vibration testing, the same pattern is also seen. Increased spindle speed leads to a sharper decrease in S/N ratio, indicating that vibration increases as speed increases. The return velocity parameter showed the greatest Delta, making it the dominant factor against vibration compared to the specimen. The consistency of the S/N ratio decline in both responses roughness and vibration confirms that the use of a spindle speed of 700 rpm provides the most stable cutting conditions in the cutting configuration of this study. At roughness, this level results in the smoothest surface, while at vibration it is still at operationally acceptable conditions. Therefore, a speed of 700 rpm can be recommended as the most effective operating parameter to obtain the best turning quality under similar conditions.

4. Conclusion

Based on the results and discussion in this study, it can be concluded that: This study demonstrates that spindle speed is the dominant parameter influencing surface roughness and tool vibration in the turning of ST 41 steel using an HSS-Co (5% cobalt) cutting tool. Increasing the spindle speed from 100 rpm to 700 rpm consistently reduced surface roughness from 21.62 µm to 9.31 µm, indicating a significant improvement in machining quality. Based on the Taguchi method analysis, spindle speed has the greatest influence on the Signal-to-Noise (S/N) ratio with the *smaller is better* characteristic. The decrease in the S/N ratio indicates that higher spindle speeds contribute directly to the reduction of surface roughness. In terms of vibration response, increasing spindle speed leads to higher vibration values; however, the vibration remains within a stable condition (*forced vibration*) and does not develop into chatter, thus not degrading surface quality. The optimal condition was achieved at a spindle speed of 700 rpm with a depth of cut of 0.5 mm, resulting in minimum surface roughness and an acceptable level of vibration. Practically, these findings contribute to the selection of effective cutting parameters to improve surface quality in conventional turning processes, particularly when using HSS-Co tools in small- to medium-scale industries. Future studies are recommended to investigate the effects of other machining parameters, such as feed rate and depth of cut, as well as to analyze parameter interactions and vibration characteristics in greater detail, including chatter identification, in order to achieve a more comprehensive understanding of machining stability.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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