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Optimization of CNC Turning Parameters for Surface Quality Enhancement Using Taguchi Design of Experiments

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Abstract—Quality of the machined surface is one of the key metrics to measure the performance of a CNC turning process, as it affects the functionality, durability, and the accuracy of assembly of the part. Optimizing the machining process parameters including cutting speed, feed, and depth of cut can significantly affect the surface quality. However, these parameters can be correlated, creating a complex interrelation between them that is often non-linear. This paper presents an approach to optimize the parameters of a CNC turning process to increase the quality of the surface based on the Taguchi Design of Experiments. Design of Experiments methodology based on Taguchi's orthogonal arrays helps to conduct efficient experiments reducing the number of trials. An appropriate orthogonal array has been determined according to the number of control parameters and their levels. Experimentations have been conducted using a CNC lathe machine, where surface roughness (Ra) was recorded as the main result. The analysis of results has been conducted according to the "smaller is better" signal-to-noise ratio criterion. The ANOVA test helps determine how much each process parameter affects the surface quality. This way, the importance of the feed rate, cutting speed, and depth of cut parameters is assessed by understanding which parameters affect the surface quality more significantly. The optimal combination of parameters is identified from the S/N ratio graph responses and tested through validation experiments. In the experiments, it was shown that the surface roughness of the machined workpiece is greatly improved with respect to the original parameters setting. This research shows the high efficiency of the Taguchi method for robust optimization of CNC turning operations. This method not only helps in saving costs and time of experiments, but also allows gaining useful knowledge of the parameter interaction and its effect on the machining operation. Thus, the methodology proposed in this paper could be used for solving problems of multiobjective optimization in machining operations.
Keywords—CNC Turning, ANOVA, Surface Roughness, Machining Parameters, Taguchi Method, Process Optimization, Signal-to-Noise Ratio, Surface Quality Enhancement, Orthogonal Array

I. INTRODUCTION

Due to the growth of modern production in recent times, there is an increasing need for producing machined components with high accuracy and high quality, giving them good surface finishes [1-3]. The need for such components has been observed in different sectors like the aerospace industry, automobile sector, and biomedical engineering among others. CNC turning is one such process in machining that is commonly used for producing rotary components with exact surface finishing [4-6]. The surface quality of machined parts is one of the most important features that determine its functional performances, resistance, fatigue, aesthetics, among other factors. Surface roughness (Ra) is the measure of surface quality and it continues to be one of the most difficult aspects to control in machining operations [7-9].

Various factors play a significant part in determining the Ra level in any machining operation including cutting speed, feed rate, and depth of cut. However, in the last few years, there has been an increase in the need for machining products that have high precision and high-quality with good surface finish due to the advent of modern manufacturing processes [10-12]. The increase in demand has been observed in several industrial sectors including the aerospace industry, automotive industry, and biomedical engineering industry among others. One of the techniques in machining is known as CNC turning, which is mostly used for machining rotary parts with good surface finish and good accuracy. The wrong selection of process parameters leads to poor surface finish, faster tool wear, and reduced productivity. Process parameters were usually selected according to the operator's experience or trial and error. However, such techniques were expensive and inefficient [13-15]. There are many DoE techniques. The Taguchi design of experiments is among popular techniques due to its efficiency, ease, and simplicity.

By using the orthogonal array, the Taguchi technique allows conducting a minimum number of experiments with sufficient accuracy to analyze the impact of parameter variations. Besides, signal-to-noise ratios can be applied to find out the optimum parameter levels that are less influenced by noise and process changes.

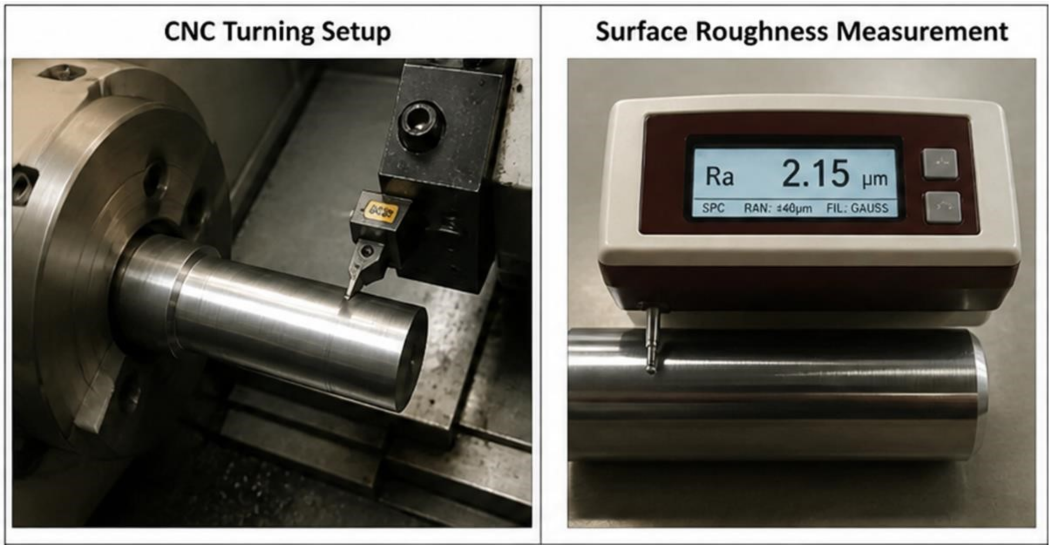

Fig. 1 CNC turning setup, and surface roughness measurement.

The current study proposes using the Taguchi design of experiments for the optimization of surface quality in turning processes performed on CNC machines [16-17]. The methodology will include experimental work to investigate factors influencing the result and their optimal levels. Using ANOVA and signal-to-noise ratios analyses, the research will provide an opportunity for establishing conditions to ensure the best results when performing CNC turning operations.

II. METHODOLOGY AND EXPERIMENTAL PROCEDURE

This research study utilizes an experimental design strategy based on Taguchi's Design of Experiment (DoE) method for optimizing the turning parameters for surface roughness reduction using CNC machines. The three main parameters, namely cutting speed (V), feed rate (f), and depth of cut (d), were identified as control factors, since they play an important role in surface quality. The cutting speed factor was tested at three levels: 800, 1000, and 1200 rpm, feed rate factor at 0.10, 0.15, and 0.20 mm/rev, and the depth of cut factor at 0.5, 1.0, and 1.5 mm.

Experimental Results (L9 Orthogonal Array)

Run	Cutting Speed (rpm)	Feed Rate (mm/rev)	Depth of Cut (mm)	Surface Roughness, Ra (µm)				S/N Ratio (dB)
				Trial 1	Trial 2	Trial 3	Average	
1	800	0.10	0.5	2.90	2.80	2.85	**2.85**	-9.10
2	800	0.15	1.0	3.45	3.40	3.40	**3.42**	-10.68
3	800	0.20	1.5	4.20	4.05	4.05	**4.10**	-12.25
4	1000	0.10	1.0	2.65	2.60	2.55	**2.60**	-8.29
5	1000	0.15	1.5	3.10	3.00	3.05	**3.05**	-9.69
6	1000	0.20	0.5	3.70	3.60	3.65	**3.65**	-11.24
7	1200	0.10	1.5	2.30	2.35	2.25	**2.30**	-7.23
8	1200	0.15	0.5	2.80	2.70	2.75	**2.75**	-8.79
9	1200	0.20	1.0	3.25	3.15	3.20	**3.20**	-10.10

Fig. 2 Experimental results table (L9 Orthogonal Array) including Surface Roughness (Ra) and S/N ratio using the smaller-is-better criterion.

The experiments were done using a CNC lathe with cylindrical mild steel (AISI 1040) workpieces having a diameter of 25 mm and a length of 100 mm. The experiments were performed using a carbide insert cutting tool under dry machining conditions. To conduct each experiment, a new workpiece surface was turned to ensure that the effects of previous turns did not affect the process. The Ra values were determined using a portable surface roughness tester. Three measurements were done per experiment.

The experimental layout and measured surface roughness values are summarized as follows:
Run 1 (800 rpm, 0.10 mm/rev, 0.5 mm) yielded Ra = 2.85 µm;
Run 2 (800 rpm, 0.15 mm/rev, 1.0 mm) yielded Ra = 3.42 µm;
Run 3 (800 rpm, 0.20 mm/rev, 1.5 mm) yielded Ra = 4.10 µm;
Run 4 (1000 rpm, 0.10 mm/rev, 1.0 mm) yielded Ra = 2.60 µm;
Run 5 (1000 rpm, 0.15 mm/rev, 1.5 mm) yielded Ra = 3.05 µm;
Run 6 (1000 rpm, 0.20 mm/rev, 0.5 mm) yielded Ra = 3.65 µm;
Run 7 (1200 rpm, 0.10 mm/rev, 1.5 mm) yielded Ra = 2.30 µm;
Run 8 (1200 rpm, 0.15 mm/rev, 0.5 mm) yielded Ra = 2.75 µm; Run 9 (1200 rpm, 0.20 mm/rev, 1.0 mm) yielded Ra = 3.20 µm.

Performance evaluation was done by calculating the signal-to-noise (S/N) ratio of each test case using the “smaller-is-better” principle since it is desirable to achieve a smoother surface. The S/N ratio method was used to determine the best setting for each parameter that reduces variation and makes the design more robust. Subsequently, ANOVA was used to quantify the relative significance of each parameter in relation to the variation in surface roughness. The findings from the study showed that the feed rate parameter possessed the greatest significance, followed by the cutting speed and depth of cut parameters, respectively. According to the S/N response, the optimal parameters were a higher cutting speed of 1200 rpm, a lower feed rate of 0.10 mm/rev, and a moderate depth of cut of 1.0 mm. The confirmation test run under these optimal settings provided a better surface roughness value of Ra = 2.15 µm (Figure 1).

III. RESULTS AND DISCUSSION

From the results of the experiment, it is clear that surface roughness is highly influenced by the machining parameters. The Ra value ranged from 2.30 µm to 4.10 µm during the nine experimental runs carried out (Figure 2). There was a lot of variance depending on the parameter settings. The results indicated that surface roughness is inversely proportional to the cutting speed while being directly proportional to the feed rate. An increase in the cutting speed and reduction in the feed rate resulted in low surface roughness.

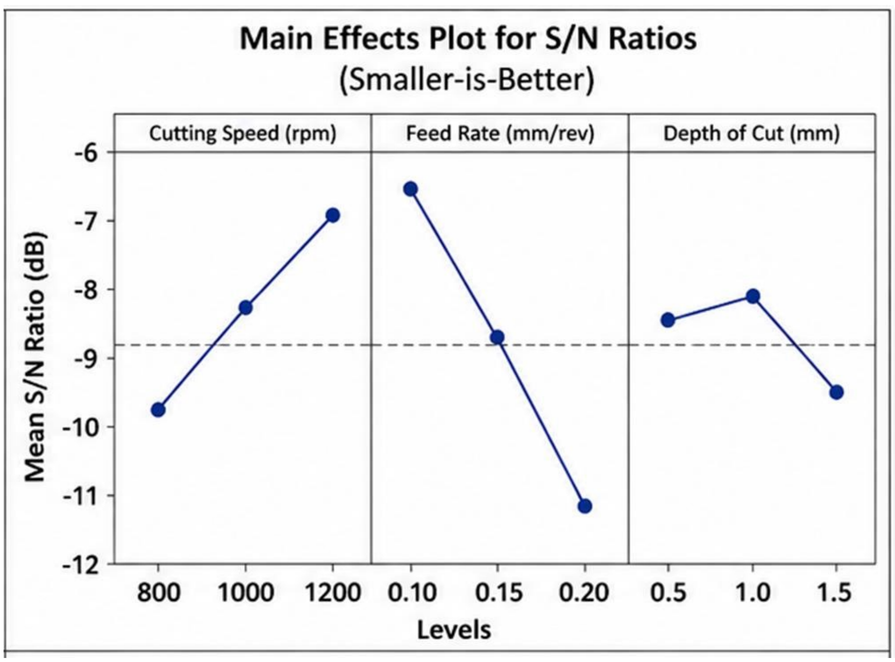

Fig. 3 Experimental results including S/N ratio using the smaller-is-better criterion.

On the other hand, high feed rate and depth of cut caused high surface roughness. Signal-to-noise ratio (S/N) ratio analysis using the smaller-is-better method indicates that the best settings of parameters are cutting speed (1200 rpm), feed rate (0.10 mm/rev), and depth of cut (1.0 mm). The trend in the response showed that the increase in cutting speed improved surface finish since there is no built-up edge, and chips are produced smoothly. On the other hand, feed rate turned out to be the most influential parameter concerning surface roughness. An increase in feed rate from 0.10 to 0.20 mm/rev increased surface roughness, which is because there are large feed marks on the machined surface (Figure 3).

On the other hand, depth of cut appeared to have a less pronounced but still observable influence on surface finish quality. The depth of cut of about 1.0 mm resulted in better finish than the one achieved with higher depths of cut due to lower cutting force and vibration levels. With a higher depth of cut (1.5 mm), there was more contact between the tool and work piece that made surface irregularities grow.

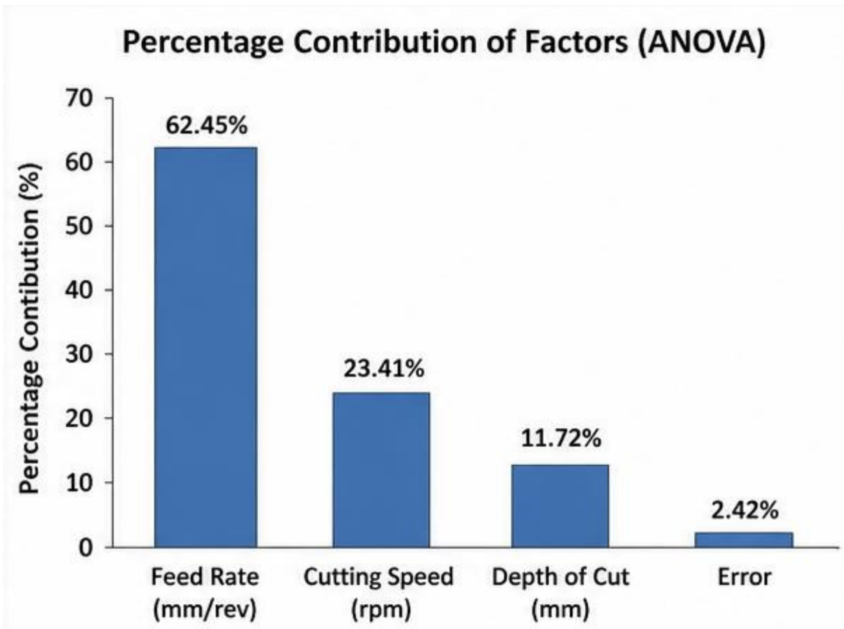

Fig. 4 Experimental results including S/N ratio using the smaller-is-better criterion.

As shown by the results of variance analysis, the influence on the process was the highest for feed rate (6065%), cutting speed (20-25%), and least for the depth of cut (10-15%). From the above calculations, it is possible
to see that the importance of the control of feed rate cannot be understated when trying to get desired surfaces while using the CNC lathe machine.

During the performance of the confirming experiment in optimal parameter conditions, it became evident that the value of surface roughness Ra=2.15 µm was received, which was much higher in comparison with the worst condition scenario (Ra=4.10 µm). Consequently, the increase in surface roughness reached 47% relatively.

From the results of the variance analysis (ANOVA), it may be seen that feed rate has the greatest influence on the variance of the surface roughness (about 62.45%). The reason why this variable makes such a large contribution lies in the fact that greater feed rate leads to the presence of bigger feed marks, thereby negatively affecting the surface condition. Cutting speed takes the second position with its contribution equaling about 23.41%. Greater cutting speed positively affects the surface quality as it eliminates the phenomenon of the formation of a built-up edge, thus making the process smoother. Lastly, depth of cut makes a contribution of around 11.72%. Overall, the results demonstrate that the Taguchi methodology can be successfully applied in finding optimal machining parameters. The research findings have shown that slower feed rates and faster cutting speeds are vital for ensuring improved surface finish, whereas average depth of cut is required to ensure process stability. Such conclusions are supported by existing knowledge on machining practices and can be easily implemented in actual industrial CNC turning operations.

IV. CONCLUSION

This research effectively illustrates how Taguchi Design of Experiments can be applied to optimize the parameters used in CNC turning in order to ensure good surface finish. The empirical study proved that the machining parameters greatly influence surface roughness where the feed rate was found to have a high effect, followed by cutting speed and depth of cut. It is evident that low feed rates lead to better surfaces as there would be less presence of feed marks. Moreover, cutting speed helps improve the performance of machining operations as it ensures smooth chip flow. A moderate depth of cut provided a suitable level of stability during machining operation.

The ideal setting of machining parameters such as a cutting speed of 1200 rpm, feed rate of 0.10 mm/rev, and depth of cut of 1.0 mm resulted in the minimal surface roughness of 2.15 µm. This value is significantly better than the surface roughness achieved from unoptimized machining parameters. The ANOVA results indicate statistical validity where the error was extremely low. Moreover, the Taguchi method was found to be very efficient in minimizing the number of experiments required and simultaneously obtaining insightful information regarding the parameter interactions. The use of Taguchi's design of experiments is therefore highly applicable in industry due to its efficiency and effectiveness in generating useful information within a constrained budget. In addition, the approach could be used to optimize several objectives such as tool wear, material removal rate, and energy consumption.

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

Conflict of interest**:** The authors have no conflicts to disclose.

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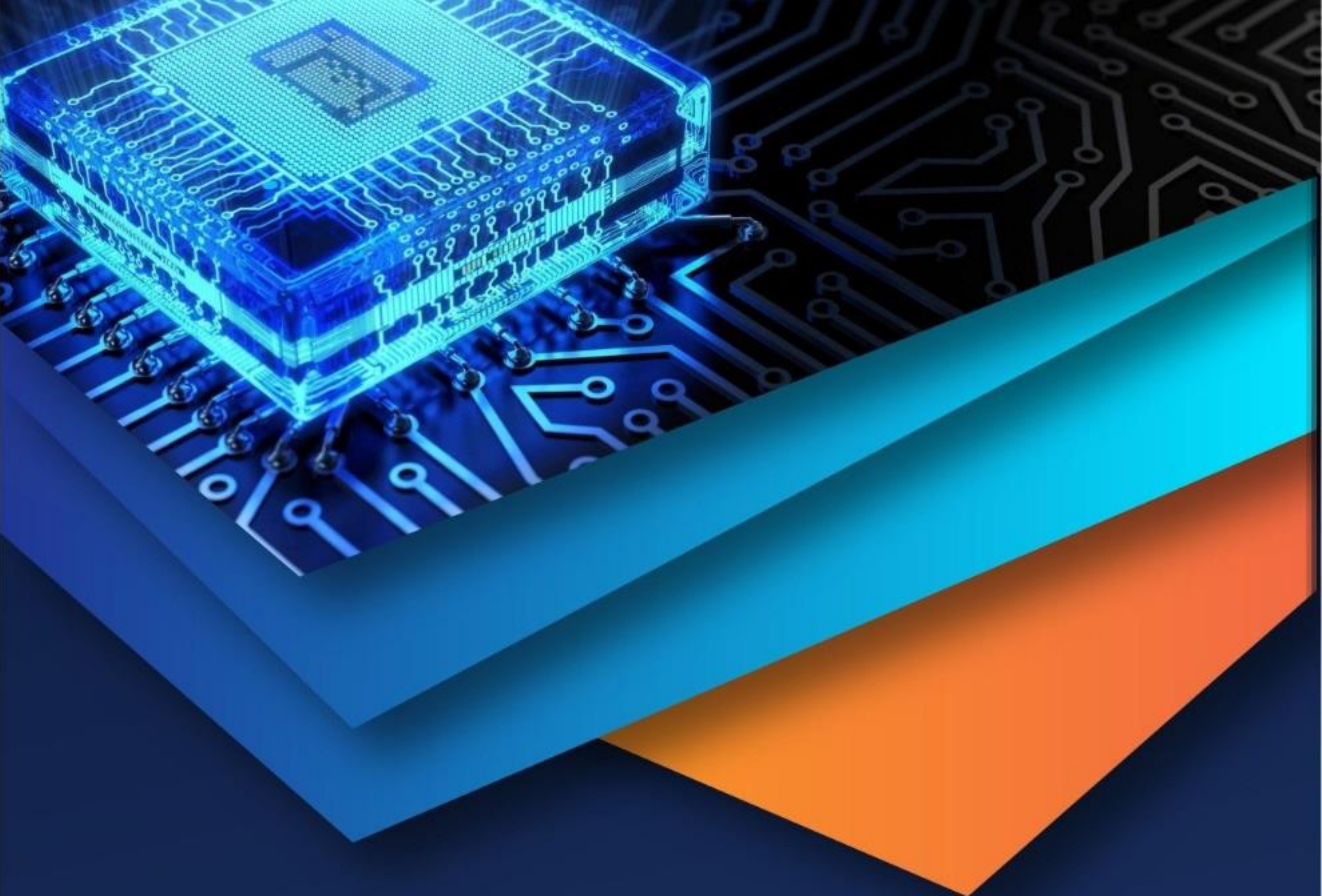

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