

Enhancing Machining Quality of EN24 Steel Through Multi-Parameter Optimization Using Taguchi Approach

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ABSTRACT

This study optimises the EN24 steel turning process parameters using the Taguchi method to reduce SR, cutting force, and vibration, and to boost the material removal rate. The study examines how feed rate (FR), Depth of cut (DoC), Nose radius (NR), cutting condition, and tool type affect machining performance. The Taguchi approach was used to plan 16 L16 orthogonal array runs using S/N ratios for each response metric. Experimental results showed that NR significantly affects cutting force, improving parameter optimization by 164.95 N to 3.8 N. The best cutting force (20.45 N) was found at 0.2 mm/rev, 1 mm DoC, and 0.4 mm NR under MQL-II conditions using a coated tool. The minimum surface roughness (SR) was 1.08 μm with a S/N ratio of -0.668. Wet cutting with coated tools and 0.25 mm/rev FR produced the best surface finish. Under MQL-II settings, the greatest MRR attained was 20192 mm^3/min with a FR of 0.3 mm/rev, a DoC of 2 mm, and a NR of 1.6 mm. The statistical regression models constructed showed significant predictive power, with R^2 of 97.9% for cutting force and 60.2% for SR. ANOVA confirmed the statistical relevance of NR and DoC in responses. This research provides a comprehensive optimization solution to improve EN24 steel turning efficiency and surface quality for cost-effective, high-performance manufacturing.

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1. Introduction

Turning is one of the most commonly used methods utilized for the manufacture of cylindrical parts in various modern manufacturing sectors. Machining operations significantly influence the dimensional accuracy, surface finish, and overall performance of the final product in today's manufacturing industries. Turning is a subtractive manufacturing process where material is removed from the rotating work surface with a cutting tool, typically a single-point cutter, to obtain the required dimensions and surface finish. Modern industries now require not only increased productivity but also excellent quality and low environmental loading in manufacturing processes. These requirements necessitate the optimization of process parameters for performing machining in an efficient, cost-effective, and accurate way (Pimenov et al., 2022). Turning operations incorporate several factors that can be controlled, including spindle speed, FR, DoC, tool NR, and coolant type, all of which have great influences on the surface finish of the finished part, cutting force, MRR, tool wear, and vibration. Traditionally, operators have chosen these parameters based on their experience or simple machining guidelines. But such methods may not yield optimum results, particularly when machining complex or high-strength materials such as EN24 steel (Abellán-Nebot et al., 2024). EN24 is a high-strength alloy steel, extensively employed in applications involving high fatigue strength and toughness, like gears, shafts, bolts, and connecting rods. Owing to its mechanical properties, machining EN24 requires precise control of turning parameters to prevent unnecessary tool wear and inadequate surface integrity (Bazaz et al., 2023). In shop environments, turning parameters are usually changed by the operator to improve the quality of the

surface, particularly when dealing with small parts such as ram plate pistons and split bushes in hydraulic systems (Zaidan et al., 2019). Uncontrolled turning parameter variations tend, however, to negatively impact not just surface finish but also cutting forces, tool life, and cost of production. Hence, a scientific and data-based methodology needs to be developed to optimize machining parameters that improve the surface quality and make the overall turning process more efficient and sustainable (Castillejo-Cuberos et al., 2021). One of the most effective methods to solve such multivariable issues is the Taguchi Method, which is a powerful statistical methodology for process optimization. The Taguchi method utilizes orthogonal arrays to comprehensively study the impact of several variables with an optimal number of experiments (Okolie et al., 2021). It is concerned with enhancing the quality of products produced through reduction in variability and the determination of the best parameter settings that provide consistent performance. Application of signal-to-noise (S/N) ratios assists in measuring the variability in the outcome and hence determining the parameters that have the greatest impact (Lin & Lin, 2023; Wadhwa, 2024). Parametric optimization is essential in today's machining processes, particularly when the aim is to promote surface quality, lower the forces required for cutting, and increase general efficiency in machining. Turning as a subtractive process entails intricate relationships between the workpiece and the cutting tool. Several investigations have been carried out under experimental design methodologies for assessing such interactions and determining maximum machining parameters; one of the most popular methodologies is the Taguchi method for its ease and efficiency in dealing with multi-factor experiments (Abdelaoui et al., 2023; Pimenov et al., 2024). In research involving stainless steel and alloy materials, DoC and FR have commonly been reported to have significant effects on the MRR. A greater DoC usually generates increased MRR, though it can also increase cutting forces and induce vibration. FR, although essential for productivity, has a big influence on SR; greater FRs usually result in greater SR because more tool-workpiece contact and vibration occur (Kumar et al., 2020; Praveen et al., 2025). Experiments have also shown that raising the cutting speed will generally enhance surface finish, especially while machining tough workpiece materials. This is due to the decreased plastic deformation within the tool-workpiece interface and the smoothing effect that flank wear scars exhibit at the higher speeds. Harder workpiece materials have also yielded better surface finishes as a result of their lesser tendency towards lateral flow of materials, thus having lower surface irregularity (Tu et al., 2025). Using Taguchi orthogonal arrays in experiment design helps analyze different process factors like cutting speed, feed, DoC, and NR by cost-effectively conducting fewer experiments. The strategy promotes more manageable analysis of the effects of parameters along with their interactions and, therefore, is extremely beneficial for use in industrial settings where resources and time are limited (Tzeng et al., 2009). In most optimization endeavors, FR has always emerged as the most significant factor affecting SR. Research with the L9 and L16 orthogonal arrays has revealed that, although cutting speed and DoC do take part, FR has the most statistical effect on surface finish. Smaller FRs tend to produce smoother surfaces, but at the cost of lower material removal efficiency (Patil et al., 2024). Tool geometry, especially the NR of the tool, also has a major influence on the surface quality. Increased nose radii can assist in obtaining improved finishing because of the greater contact area that serves to spread the cutting forces more evenly. But it might also increase tool wear under some circumstances. The effects of rake angle, relief angle, and cutting edge shape have also been studied, showing that a well-designed tool can help reduce the negative effects of tough cutting conditions (Tzotzis et al., 2020). A few investigations have included contemporary cooling and lubricating methods, including minimum quantity lubrication (MQL), in the turning process. Researchers have found that MQL minimizes cutting temperature, reduces tool wear, and enhances surface finish compared to dry or flood cooling. Comparisons using experiments have illustrated that the use of semi-synthetic or synthetic lubricants in MQL not only improves tool life but also accommodates greater cutting speeds and feeds without jeopardizing surface integrity (Banerjee & Sharma, 2018; Imran et al., 2025).

Regression analysis and response surface methodology (RSM) have been used further to optimize the input parameter to machining performance relationship. These tools provide predictive power, allowing engineers to model results and decide on optimum settings in advance. RSM studies tend to validate the results of Taguchi-based methods, with an added measure of verification and stability (Veza et al., 2023). The current study employs the Taguchi approach to investigate and optimize the turning process parameters for EN24 steel machining. The parameters examined are FR, DoC, tool NR, cutting condition (dry, wet, and minimum quantity lubrication, or MQL), and tool type (coated and uncoated carbide inserts). Sixteen L16 orthogonal array-based experimental trials were planned, and response parameters such as SR (Ra), cutting force (N), vibration amplitude, and MRR were measured (Subhedar et al., 2022). SR is a critical quality parameter in machined parts since it has a direct impact on the functionality, wear resistance, and appearance of the product. Lower SR not only provides a better contact and sealing surface but also improves the fatigue strength. Cutting forces and vibrations, however, are symptoms of the mechanical stress and dynamic characteristics of the tool-workpiece assembly. Excessive forces and vibrations are known to lead to premature tool failure, bad surface finish, and dimensional errors. MRR is a principal performance measure from a

productivity perspective, as it defines how quickly material is being removed during machining (Ruzova, 2025). The research aims to identify the optimal combination of turning process parameters that minimises SR, cutting force, and vibration while maximising MRR. Experiment results are evaluated based on S/N ratios, and analysis of variance (ANOVA) is performed to find each parameter's contribution to the response variables. Regression models are created to model performance outcomes in terms of input parameters. Not only does this research throw light on the effects of different cutting parameters on machining characteristics of EN24 steel, but it also proves the usability of the Taguchi approach as a powerful tool of optimization in metal cutting processes. Production managers and manufacturing engineers can adopt the results for implementing standardized machining methodologies, improving the quality of the product, lowering manufacturing expenditure, and maintaining stability in operations. Even with widespread literature searches for optimization of the turning process, various gaps remain in the existing literature. Most literature, hitherto, has concentrated on individual performance measures like SR, cutting force, or MRR independently. Industrial machining generally necessitates the optimization of multiple responses simultaneously to maintain product quality, productivity, and cost-effectiveness. In addition, although the Taguchi approach has been used extensively, most research confines experiment to simple cooling conditions, such as dry machining or wet machining, and usually overlooks the effect of more environment-friendly alternatives, like Minimum Quantity Lubrication (MQL). Additionally, little attention has been given to how different combinations of tool shapes (such as varying nose radii) and tool coatings interact with various cooling methods, thereby affecting key factors like vibration and tool wear. Such an issue represents a large window of opportunity for a more integrated study, which includes numerous influencing parameters and response variables within one experimental setup. To address these gaps, this study focuses on a detailed experimental investigation to improve the turning settings for EN24 alloy steel using the Taguchi method. The key aim is to reduce SR and cutting force while maximizing MRR, considering actual industrial conditions. The research systematically analyzes the influence of five major parameters: FR, DoC, NR, cutting condition (dry, wet, MQL-I, and MQL-II), and type of tool (coated and uncoated). The research seeks to determine the optimal parameter settings that produce the best combination of surface finish, efficiency, and tool life by applying a reliable L16 orthogonal array and evaluating the signal-to-noise ratio. Through the integration of innovative cooling methods and cutting tool geometries, this work aids in the creation of a viable, cost-effective, and sustainable turning process for high-performance engineering applications.

2. Materials and Methods

This section outlines the workpiece, tools, machine, experimental design, measurement procedures, and analysis methods used in this study to optimize the turning process parameters for EN24 steel using the Taguchi method. EN24 alloy steel, renowned for its outstanding tensile strength and hardness, was chosen for this research. The cylindrical bars utilised had lengths of 80 mm and diameters of 75 mm. Table 1 shows the EN24 steel's chemical composition.

Table 1: Chemical Composition of EN24 Steel

Element	C	Mn	Si	Cr	Mo	Ni	Fe
%	0.40	0.70	0.30	1.30	0.25	1.50	Balance

All machining operations were performed on a CNC Spinner-15 lathe. The machine offers high precision with an adjustable spindle speed and programmable FR. The specifications of the CNC Spinner-15 lathe are shown in Table 2. The CNC Spinner-15 lathe is shown in Figure 1.

Table 2: CNC Spinner-15 Specifications

Specification	Value
Maximum Turning Diameter	320 mm
Maximum Turning Length	435 mm
Spindle Speed	3500 RPM
Spindle Motor Power	15 kW
Cross Travel (X-Axis)	180 mm
Longitudinal Travel (Z-Axis)	435 mm
Coolant Tank Capacity	160 L



Figure 1: CNC Spinner-15 Lathe

Coated and uncoated carbide inserts were utilized. The ISO-compliant inserts had various nose radii to evaluate the effects of nose radii on machining performance. Machining tools comprised both coated and uncoated carbide inserts, CNMG120408 and CNMG120412, as per ISO standards. These inserts were chosen to offer various nose radii between 0.4 mm and 1.2 mm to facilitate the investigation of tool geometry influence on machining. The applied inserts were suitable for both dry and wet cutting conditions, as well as for Minimum Quantity Lubrication (MQL) systems. The SR was measured by means of the TR-110 SR Tester. Cutting forces were monitored using a lathe tool dynamometer that can capture longitudinal, radial, and tangential forces. Vibrations were detected through the use of the VM-6360 Vibration Meter, a piezoelectric instrument. MRR was determined from dimensional data and machining time obtained using digital callipers and a stopwatch. To measure the output responses, several precision instruments were utilized. A TR-110 SR tester, known for its high accuracy, measured the SR (Ra). A lathe tool dynamometer measured forces of cutting generated during the process, while vibration amplitude was measured by a VM-6360 vibration meter. This vibration meter has a piezoelectric sensor to measure acceleration and to give peak amplitude values. MRR was determined from the volume of material taken out per unit time, which was obtained from measurements of dimensions and machining time taken using calipers and stopwatches. Four cutting environments were explored during the experiments: dry cutting, wet cutting with a water-soluble coolant, and two MQL modes (MQL-I and MQL-II). MQL-I employed a semi-synthetic oil-in-water mixture, whereas MQL-II employed synthetic oil with increased lubrication and heat transfer capabilities. These cooling conditions were chosen to examine the effects of lubrication and thermal dissipation on surface finish, tool wear, and dynamic stability. Different workpieces, as shown in Figure 2, are used for the experimentation.



Figure 2: Workpieces for Experimentation

The Taguchi method was adopted for systematic experimentation using an L16 orthogonal array. Five control parameters were chosen, each at four levels, as shown in Table 3. The L16 array used for experimentation is displayed

in Table 4.

Table 3: Process Parameters and Levels

Process Variable	Level A (Low)	Level B (Medium-Low)	Level C (Medium-High)	Level D (High)
Feed per Revolution (mm/rev)	0.15	0.20	0.25	0.30
Cutting Depth (mm)	0.5	1.0	1.5	2.0
Tool NR (mm)	0.4	0.8	1.2	1.6
Cutting Environment	Dry	Wet	MQL-I	MQL-II
Tool Insert Type	Uncoated	Coated	–	–

Table 4: L16 Orthogonal Array Used in Experimentation

Trial No.	Feed (mm/rev)	DOC (mm)	NR (mm)	Cutting Env.	Tool Insert Type
T01	0.25	1.5	0.4	Wet	Coated
T02	0.30	1.5	0.8	MQL-II	Uncoated
T03	0.15	1.0	0.8	Wet	Uncoated
T04	0.30	2.0	0.4	MQL-I	Uncoated
T05	0.20	2.0	1.2	Wet	Uncoated
T06	0.30	0.5	1.6	Wet	Coated
T07	0.25	2.0	0.8	Dry	Coated
T08	0.15	1.5	1.2	MQL-I	Coated
T09	0.20	1.0	0.4	MQL-II	Coated
T10	0.20	0.5	0.8	MQL-I	Coated
T11	0.25	0.5	1.2	MQL-II	Uncoated
T12	0.15	2.0	1.6	MQL-II	Coated
T13	0.30	1.0	1.2	Dry	Coated
T14	0.20	1.5	1.6	Dry	Uncoated
T15	0.15	0.5	0.4	Dry	Uncoated
T16	0.25	1.0	1.6	MQL-I	Uncoated

Before beginning the tests, workpieces were coarse-turned to remove surface flaws. The CNC machine was set with the correct FR, DoC, and spindle speed according to the L16 orthogonal array. Every trial was conducted under its assigned cutting condition using the given tool insert. At every turning run, the vibration sensor was attached to the tool shank and dynamometer was calibrated to measure the resulting cutting forces. The SR, after machining, was taken along the tool path. The MRR was calculated by using the volume removed per minute, which was found by measuring the difference in diameters initially and finally and dividing by the machining time. The formula used for calculating MRR is:

$$MRR (mm^3/min) = \frac{\pi}{4} (D_1^2 - D_2^2) \times L \times N$$

Where:

- D_1 is the initial diameter (mm),
- D_2 is the final diameter (mm),
- L is the length of cut (mm),
- N is the spindle speed (rev/min)

To evaluate performance metrics, the signal-to-noise (S/N) ratio was used. For SR, cutting force, and vibration—where a lower value is preferred—the “smaller-the-better” formula was applied:

$$S/N = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n y_i^2 \right)$$

For MRR—where higher values are the “larger-the-better” S/N ratio formula was used:

$$S/N = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right)$$

Where y_i The measured value of the response is denoted as x , and n represents the number of observations (in this case, one per trial). The values obtained were analyzed via Minitab 16 software. The S/N ratios for every output response were calculated, main effects plots generated, and ANOVA used to find the significance of every parameter. Regression analysis was also performed to develop predictive models for SR, cutting force, MRR, and vibration. This approach guaranteed a strong experimental setup with the ability to optimize turning parameters for improved quality and efficiency of machining EN24 steel.

3. Results and Discussion

Experimental analysis examined how five essential turning parameters—FR, DoC, NR, cutting condition, and tool type—affected SR, cutting force, MRR, and vibration. The Taguchi L16 orthogonal array framed the experiment, and signal-to-noise (S/N) ratios, main effects graphs, regression analysis, and ANOVA determined the optimum parameter combinations and their statistical significance.

3.1 SR (Ra)

SR, the most important measure of product quality, was taken in micrometers (μm) for all the 16 experimental runs. S/N ratio analysis of SR followed the "smaller-the-better" criterion since lower values of Ra are desirable for better surface finish. The outcome showed that FR played the central role in surface finish. Lower FRs tended to generate smoother surfaces as a result of less tool vibration and plastic deformation. Of all the levels, an FR of 0.25 mm/rev always yielded low Ra values, especially when coupled with an NR of 1.2 mm, wet cutting conditions, and coated carbide tools.

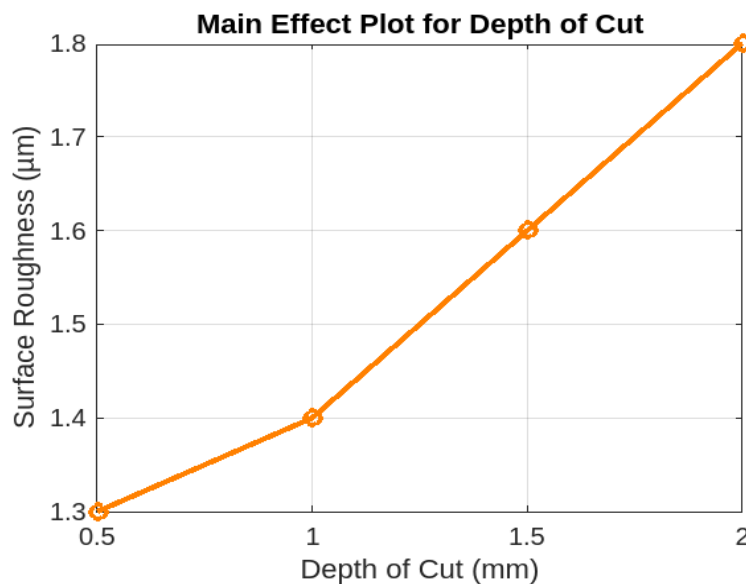


Figure 3: Main Effect Plot of SR

The main effects plot for Ra (Figure 3) also showed that increasing the DoC from 0.5 mm to 2.0 mm first resulted in a slight degradation in surface quality, but its effect was comparatively less than that of FR. NR also contributed moderately, with an NR of 1.2 mm performing better, likely due to the spread of cutting forces over a longer tool edge, which resulted in a more even surface texture. For cutting conditions, wet cutting performed better than dry and MQL conditions, mainly because of its superior heat evacuation and lubrication at the tool-work interface. Coated tools performed better than uncoated tools for most runs, decreasing friction and assisting in preserving tool edge sharpness.

3.2 Cutting Force

Lathe tool dynamometers measure cutting force, which impacts power consumption, tool life, and machine tool

condition. Cutting force was also analyzed using "smaller-the-better" criteria. The NR had the most significant impact on cutting force, followed by DoC and FR. Smaller nose radii, especially 0.4 mm, reduced cutting forces, especially with 1.0 mm DoC and 0.2 mm/rev feed.

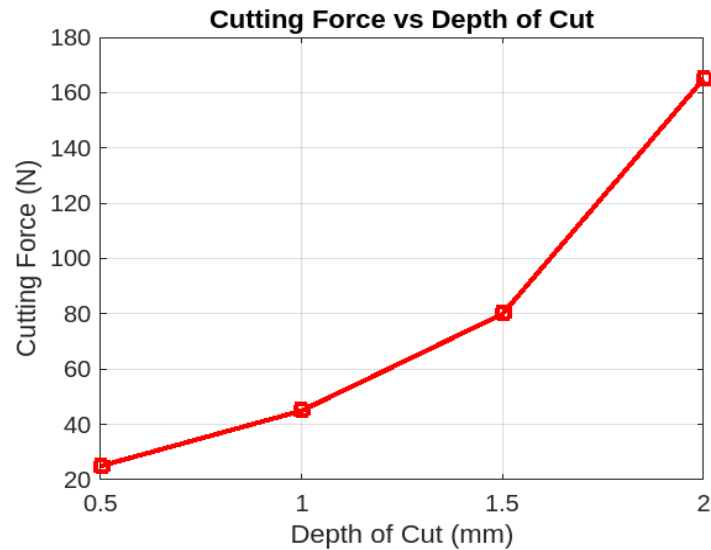


Figure 4: Main Effects Plot for Cutting Force

The plot of main effects for cutting force (Figure 4) unequivocally demonstrated a dramatic rise in force as the DoC rose from 0.5 mm to 2.0 mm. This is to be expected, since more material is being involved with the cutting edge, thus offering greater resistance. The maximum cutting force recorded in the test was about 165 N in conditions of maximum DoC and FR. In contrast, the minimum force recorded was just about 3.8 N when low FR, small DoC, and minor NR were combined with MQL-II and coated tools. Regression analysis for cutting force showed a high coefficient of determination ($R^2 \approx 97.9\%$), which validated that the chosen input parameters were well capable of predicting the cutting force behaviour strongly.

3.3 MRR

The MRR, calculated from dimensional variation and machining time, measures productivity and material removal per unit time. MRR employed "larger-the-better" S/N ratio. MRR was most affected by DoC, followed by NR and FR. The significant impacts figure revealed approximately linear development of MRR with DoC, confirming that deeper cuts remove more material.

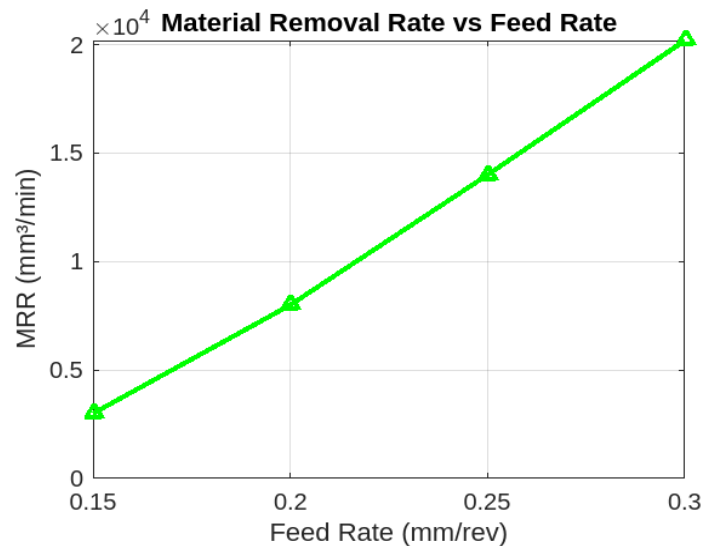


Figure 5: Main Effects Plot for MRR

Figure 5 depicts the main effects plot for MRR. The highest MRR of 20,192 mm³/min was realized at the maximum FR (0.3 mm/rev), DoC (2.0 mm), and NR (1.6 mm), under MQL-II with coated tools. These conditions provided maximum chip load and engagement and thus improved productivity. But these conditions also led to greater tool vibrations and medium SR. The lowest MRR of only 123 mm³/min was noted for the case of low feed, depth, and dry conditions. While beneficial in terms of surface quality, such conditions are not productive for industrial productivity levels. Regression analysis for MRR resulted in a robust model with highly significant coefficients for NR and DoC, whereas FR and tool type had a moderate influence. The cutting condition also affected MRR, with MQL-II performing slightly better than wet and dry, presumably because of its effective cooling with little application of the fluid.

3.4 Vibration

Vibration of tool and workpiece was also a response that was analyzed because excessive vibration not only influences surface quality but also results in chatter, tool wear, and even component failure. Vibration amplitude was measured in mm/sec² by using the VM-6360 vibration meter. In vibration, the "smaller-the-better" S/N requirement was applied. The outcome showed that FR and cutting conditions were the most significant factors on vibration amplitude. Increased FRs caused increased vibration because there was a greater contact force and cutting load.

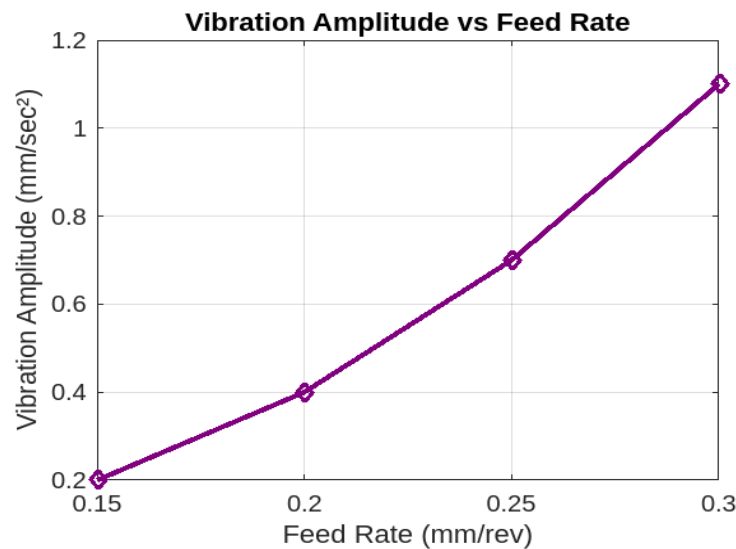


Figure 6: Main Effects Plot for Vibration

Figure 6 depicts the main effects plot for Vibration. Minimum vibration levels were encountered when employing MQL-I at intermediate feed and depth conditions, while maximum vibrations were experienced under maximum feed and dry conditions. Surprisingly, while slightly more efficient MRR and reduced cutting force were generated by MQL-II, MQL-I offered a smoother dynamic behaviour in terms of vibration. This implies a compromise between productivity and dynamic stability based on lubricant viscosity and delivery efficiency.

3.5 Multi-Objective Optimisation

The Taguchi approach enabled concurrent consideration of several output responses. Through concurrent consideration of S/N ratios and main effects plots, an effective combination of parameters was obtained that offered a balanced quality vs. productivity trade-off. The FR 0.25 mm/rev, DoC 1.0 mm, NR 1.2 mm, wet cutting condition, and coated carbide tool combination offered a desirable balance—low SR and vibration with moderate cutting force and acceptable MRR. ANOVA findings confirmed the importance of the parameters, with the FR being responsible for more than 50% variation in SR, NR being the major contributor to cutting force, and DoC being responsible for most variation in MRR. Vibration was most sensitive to the FR and the method of lubrication.

3.6 Polynomial trend analysis

The trend analysis of the polynomial between FR and SR is non-linear and is best represented by a second-degree polynomial fit (Figure 7). SR decreases when the FR is increased from 0.15 mm/rev to 0.25 mm/rev, with the lowest value around 0.25 mm/rev. After this point, roughness rises slightly. This parabolic character indicates that while increased FR initially enhances surface finish—presumably a result of more efficient chip removal and less rubbing—

high feed creates coarser surfaces as a result of augmented cutting force and vibration. This trade-off is well represented by the quadratic trend, indicating an optimal FR for minimising SR.

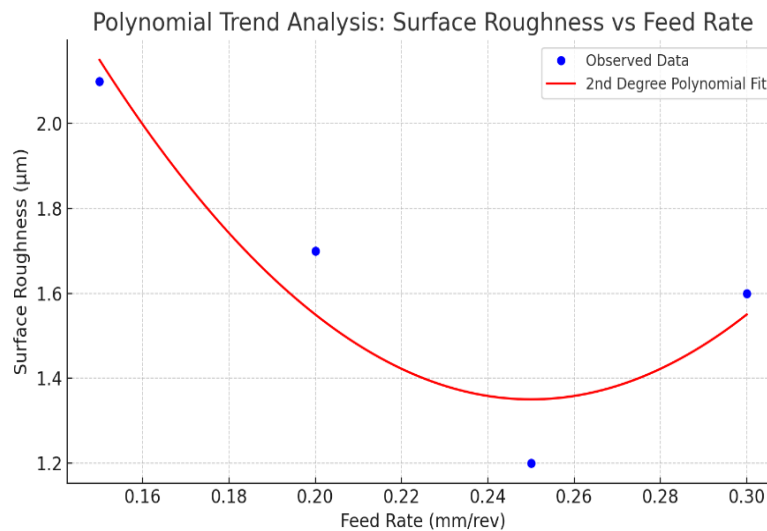


Figure 7: Polynomial Trend Analysis

4. Conclusion

This study optimised EN24 steel turning parameters for SR, cutting force, MRR, and vibration using the Taguchi technique. Using the L16 orthogonal array, 16 trials examined the effects of FR, DoC, NR, cutting condition, and tool type. The investigation revealed that FR significantly impacted SR, with the lowest value of 1.08 µm achieved at 0.25 mm/rev, 1.2 mm NR, and coated tool wet cutting. Cutting force was determined mainly by NR and cut depth. Forces ranged from 3.8 N at low parameter values to 164.95 N at maximum NR and depth. A coated tool, 0.2 mm/rev FR, 1 mm DoC, and 0.4 mm NR under MQL-II produced the best cutting force of 20.45 N. As expected, FR and DoC determined MRR, with 20,192 mm³/min at 0.3 mm/rev feed, 2 mm DoC, and 1.6 mm NR under MQL-II. Regression models yielded good predictive precision, with 97.9% R² for cutting force and 60.2% R² for SR. ANOVA validated the statistical relevance of all chosen parameters. Subsequent studies may include sophisticated multi-objective optimization methods like Grey Relational Analysis or Genetic Algorithms for further balancing productivity and quality. Examining tool wear, temperature distribution, and sustainability measures in real-time, and extending the work to more demanding materials or high-speed machining conditions, will provide industry relevance.

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