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Sustainable Approach for Comparative Analysis on Machining Effects of Mild Steel and Alloy Steel using Taguchi Design Based Pareto Optimization

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Abstract - Under sustainable machining approaches, this study presents a comparative analysis of the machining characteristics such as surface roughness and time for machining of Mild Steel and EN24 alloy steel. With increasing emphasis on environmentally responsible manufacturing, this research investigates the performance of these widely used materials when subjected to the turning operation. While EN24 contains various alloying elements that enhance its mechanical properties, including hardness and strength, Mild steel, is soft, ductile and more easily machinable. Three key lathe machining parameters, such as depth of cut, MRR, and feed rate, were analyzed using a controlled set of turning operations on a lathe in wet condition. The experimental design employed Taguchi's L9 Orthogonal array design coupled with Pareto analysis to optimize the process parameters. Results indicate that EN24, due to its higher hardness and strength,achievesa better surface finish than Mild Steel; however, by the use of proper lubrication significantly improves surface finish for both of the materials.

Keywords: **Sustainable Machining, EN24 Alloy Steel, Mild Steel, Surface Roughness, Taguchi Method**

NOMENCLATURE

MLQ	Minimum Quantity Lubrication
S/N Ratio	Signal To Noise Ratio
MCDM	Multi-Criteria Decision Making
DoF	Degrees of Freedom
Adj SS	Adjusted Sum of Squares
Adj MS	Adjusted Mean Square
F Value	F-Statistic Value
P Value	Probability Value

1. INTRODUCTION

In the modern manufacturing sector, the use of sustainable practices on industrial operations shift from traditional machining methods to environmentally friendly alternatives systems. Machining operations play a significant contribution to the manufacturing energy consumption, and it typically involves significant use of cutting fluids, which pose environmental and health risks due to their chemical composition and disposal issues. So, it is evident that improving the sustainability of this sector through resource consumption and energy reduction is an important goal. Essentially, sustainable machining seeks to balance economic viability with environmental responsibility and social well-being.

Materials such as Mild Steel, known for its low strength and hardness, and EN24 low alloy steel known for its toughness and high tensile strength, are commonly used in engineering applications. While both materials go through a turning operation on the lathe, at that time, understanding their behavior under sustainable machining conditions is essential so that their environmental impact is minimized with a maintained performance standards. Mild Steel has relatively lower hardness, is easier to machine, and exhibits less tool wear, whereas EN24 introduce challenges due to its higher strength and hardness, often results in increased tool wear and heat generation.

The main focus of this research is a comparative analysis of the Lathe machining characteristics of Mild Steel and EN24 using sustainable approaches. The key performance indicators such as surface roughness, machining time in wet machining has been evaluated in this study,by using Taguchi L9 orthogonal array design of experiment to control on input parameters such as feed rate, depth of cut, and RPM. This study aims to find the feasibility of sustainable machining practices for these materials by employing a structured experimental design and statistical analysis. This study demonstrates that this type of machining not only reduces environmental impact but can also enhance machining performance, especially when optimized for specific material properties. Hopefully, these findings will provide valuable insights for industry personnel who are seeking to adopt green manufacturing strategies without compromising productivity or quality.

2. LITERATURE REVIEW

Ajit Kumar Senapati et al. (2014) [1] investigated tool forces during dry turning of mild steel on a high-speed lathe using Taguchi's L9 orthogonal array. The parameters varied were cutting speed, feed rate, and depth of cut. Optimal conditions were 1.5 mm depth of cut, 0.69 mm/rev feed, and 525 rpm. ANOVA showed depth of cut had the greatest impact. The study effectively predicted tool forces but did not assess tool wear or surface finish.

Waghmare et al. (2024)[2] optimized ECM parameters for Al/15%SiC composites using Taguchi, ANOVA, and TOPSIS. Voltage, feed rate, and electrolyte concentration were varied in an L27 design. All factors significantly affected Ra and MRR.

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Optimal Ra at 20V, 0.4 mm/min, 30 g/L; MRR at 25V. TOPSIS and ANOVA were used.

Kishan Kumar Nirvan et al. (2020)[3] optimized surface roughness AISI 1040 mild steel using Taguchi and ANOVA on a CNC lathe with HSS tools under dry conditions. Parameters were RPM, feed rate, and depth of cut. Optimal setup: 630 rpm, 0.4 mm/rev, 0.6 mm depth. Feed rate was most influential. The study excluded factors like tool radius and lubrication.

Parray et al. (2024)[4] evaluated garlic oil-based MQL in machining EN24 steel using Taguchi on an Enterprise 1330 lathe with TNMG inserts under dry and MQL conditions. Variables: Cutting speed and lubrication type.The optimal setup was MQL at 630 rpm. ANOVA showed lubrication had the highest impact. Garlic oil MQL reduced wear by 43.8% and improved finish by 79.3%.

Saurabh et al. (2015)[5] used the Taguchi method to optimize CNC turning of aluminum alloys. The inputs were cutting speed, feed rate, and depth of cut.Surface roughness was taken as output. Tools made of uncoated carbide were used in experiments. Cutting speed had the least effect, whereas feed rate and depth of cut had the biggest. ANOVA validated the findings. The absence of real-time and multi-objective optimization, as well as the exclusion of vibration and tool wear, were among the limitations.

3. MATERIALS AND METHODS

This study evaluates the machinability of Mild Steel (MS) having 0.15–0.30 %C, offering high ductility and machinability, though not hardenable by heat treatment; EN-24 isan alloy of Ni, Cr and Mo with around 0.4% C, very strong, resists fatigue,easy to machine after annealing. Both the material of same size were machined using a HMT NH-22 semi-automatic lathe in emulsion oil atmosphere. Design of experiment prepared using Taguchi L9 orthogonal array under wet machining conditions with emulsion oil. The objective was to optimize surface roughness and machining time by putting input parameters namely RPM, feed rate, and DOC.

3.1.Experimental Parameters and Methodology

The input parameters were normalized to coded levels i.e. −1, 0, +1 for statistical analysis. The three levels of machining parameters were used as Spindle Speed (RPM) of 550, 715, 930, Feed Rate of 0.08, 0.16, 0.32 mm/rev and Depth of Cut of 0.15, 0.30, 0.60 mm.Surface roughness was measured using a SRT6200 Mextech surface roughnesstester and machining time was recorded via a stopwatch.

3.2. Analytical procedures

Signal-to-Noise (S/N) ratio, ANOVA, and regression modelling were derived using Minitab software.m For S/N ratio the goal was fixed for 'Smaller-the-better' applied to both surface roughness and machining time.The generalized statistical regression equation was derived as given form in Eq. 1.

$$Y=\beta_0+\beta_1*RPM+\beta_2*Feed+\beta_3*DOC \qquad (1)$$

Where, **Y** is the response like surface roughness, and **β** are coefficients which were calculated via least squares regression to establish predictive models. Finally the Pareto analysis were conducted to identify the dominant factors influencing output variability for both machining time and surface roughness.

4. RESULTS AND DISCUSSION

The results of experimental studies on mild steel and EN24 materials are discussed in this section.

4.1. Analysis on Mild Steel

The input and output parameter set for mild steel is given in Table 1.

Table 1. Summary of Experimental Results

Sl. No.	RPM	FEED (mm/rev)	Depth of Cut (mm)	Machini-ng Time (S)	Surface Roughness (Ωm)
1	550	0.08	0.15	32.87	0.952
2	550	0.16	0.3	18.18	3.449
3	550	0.32	0.6	9.26	3.98
4	715	0.08	0.3	26.93	0.733
5	715	0.16	0.6	14.87	3.043
6	715	0.32	0.15	8.84	1.177
7	930	0.08	0.6	23.00	0.563
8	930	0.16	0.15	11.38	0.63
9	930	0.32	0.3	6.78	0.569

4.1.1. Taguchi S/N Ratio Analysis

For Mild Steel, the signal-to-noise (S/N) ratio analysis (smaller-the-better) showed that Feed had the highest impact on both machining time and surface roughness, with the highest Delta (Maximum-minimum) value as 10.16 and Rank 1. Subsequently RPM was second and DOC was 3rd.

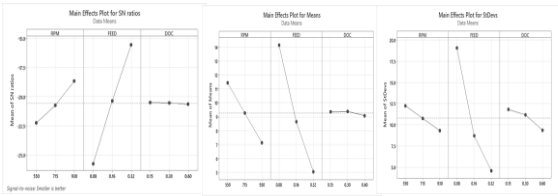

Fig.1 Main effect plot- SN Ratio, Mean&St.Dev

4.1.2. ANOVA and Regression Mathematical Modelling For machining time of MS

ANOVA analysis of machining time in Table 2 shows that feed posses the strongest influence as P value obtained as 0.003, while P value of RPM and depth of cut were statistically insignificant.

Table 2. ANOVA for machining time

Source	DoF	Adj SS	Adj MS	F-value	P-value
Regression	3	568.133	189.378	10.92	0.012
RPM	1	60.717	60.717	3.50	0.120
FEED	1	500.925	500.925	28.89	0.003
DOC	1	6.492	6.492	0.37	0.567
Error	5	86.696	17.339		
Total	8	654.829			

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In Table 3 ANOVA of surface roughness it can be derived that the RPM is significant parameter as P value is 0.035, while Feed and DOC had P-values above 0.05, indicating lower impact.

Table 3. ANOVA for surface roughness

Source	DoF	Adj SS	Adj MS	F-value	P-value
Regression	3	11.870	3.9567	4.42	0.072
RPM	1	7.411	7.4106	8.28	0.035
FEED	1	1.121	1.1207	1.25	0.314
DOC	1	3.339	3.3389	3.73	0.111
Error	5	4.472	0.8945		
Total	8	16.343			

Two mathematical regression models for mild steel are developed as shown in Eqs. 2 and 3.

$Machining\ time = 44.66 - 0.01669 \times RPM - 74.8 \times Feed - 4.54 \times DOC$ (2)

$Surface\ roughness = 4.12 - 0.00583 \times RPM + 3.54 \times Feed + 3.26 \times DOC$(3)

4.1.3. Model Validation for MS

Experimental and predicted results in Fig. 2 were compared and for machining time the regression model's prediction was found to be very close, with a percentage error of 4% to 45%. For surface roughness more variation is visualizedand the errors in the predictions were between 0.5% and more than 130%, which means there was more variability.

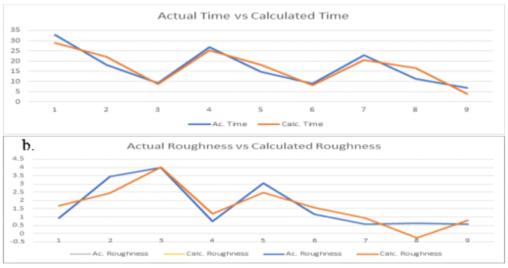

Fig. 2 Actual vs predicted(a) time & (b) roughness

4.1.4 Pareto Analysis for MS

Fig 3. depicts that Feed posses the highest significance on both i.e response parameters as the P value is 0.003. However RPM showed moderate influence and DOC was statistically insignificant.

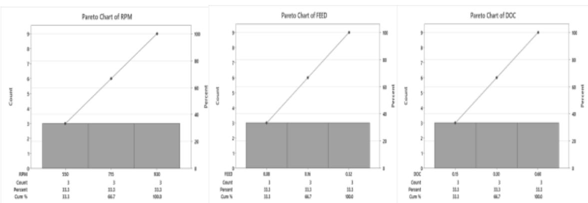

Fig. 3 Pareto analysis for RPM, Feed & DOC

4.2.Analysis on EN24 Steel

The input and output parameter set for EN24 steel is given in Table 4.

Table 4. Summary of Experimental Results

Sl. No.	RPM	FEED (mm/rev)	Depth of Cut (mm)	Machining time (S)	Surface Roughness (Ωm)
1	550	0.08	0.15	34.60	4.17
2	550	0.16	0.30	16.86	7.07
3	550	0.32	0.60	11.73	7.28
4	715	0.08	0.30	27.11	5.28
5	715	0.16	0.60	13.80	4.27
6	715	0.32	0.15	8.10	7.38
7	930	0.08	0.60	22.96	3.31
8	930	0.16	0.15	10.92	5.55
9	930	0.32	0.30	9.24	7.57

4.2.1. Taguchi S/N Ratio Analysis

Similar to Mild Steel, the Taguchi analysis for EN24revealed Feed as the most influential parameter as the Delta value found as 7.46, Rank 1, followed by RPM and then DOC as shown in Fig.4.

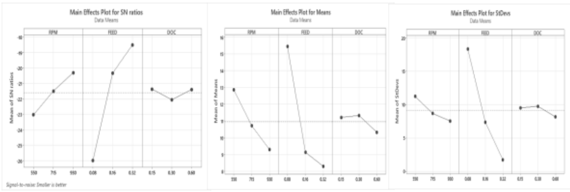

Fig.4 Main effect plot of SN Ratio, Mean& St.Dev

4.2.2.ANOVA and Regression Mathematical Modelling For machining time of EN24 steel

It is observed from ANOVA for machining time in Table 5 that the regression model and feed are significant as P value is 0.043 and 0.11 respectively. However, RPM (P value 0.229) and DOC (P value 0.663) were insignificant.

Table 5. ANOVA for machining time

Source	DoF	Adj SS	Adj MS	F-value	P-value
Regression	3	522.373	174.124	5.90	0.043
RPM	1	55.356	55.356	1.87	0.229
FEED	1	460.693	460.693	15.60	0.011
DOC	1	6.325	6.325	0.21	0.663
Error	5	147.623	29.525		
Total	8	669.996			

It is observed from ANOVA of surface roughness in Table 6 that the regression model and feed are highly significant as the P value is 0.001 and P = 0.000 respectively. Feed is the dominant factor for surface roughness. RPM and DOC are found as insignificant as the P value is 0.101 and 0.882 respectively.

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Table 6. ANOVA for surface roughness

Source	DoF	Adj SS	Adj MS	F-value	P-value
Regression	3	34.6566	11.5522	32.94	0.001
RPM	1	1.4159	1.4159	4.04	0.101
FEED	1	33.2322	33.2322	94.77	0.000
DOC	1	0.0086	0.0086	0.02	0.882
Error	5	1.7533	0.3507		
Total	8	36.4100			

Two equations are formulated for machining time and surface roughness of EN24 steel as shown in Eqs. 4 & 5.

$$Machining\ time = 44.04 - 0.0159 \times RPM - 71.7 \times Feed - 4.48 \times DOC \quad (4)$$

$$Surface\ roughness = 2.72 - 0.00255 \times RPM + 19.26 \times Feed + 0.17 \times DOC \quad (5)$$

4.2.3. Model Validation of EN24 steel

Experimental and predicted values were compared for machining time and surface roughness. The regression predictions closely followed experimental trends with errors generally under 35%. For surface roughness good agreement was observed in mid-range values. Percentage errors in predicted roughness were within ~3–24%, showing better consistency than the Mild Steel model.

Fig. 6 Actual vs predicted(a) time & (b) roughness

4.2.4. Pareto Analysis for EN24 steel

Fig. 5 shows that feed is most significant factor across both machining time and surface roughness, whereas RPM and DOC were relatively less impactful.

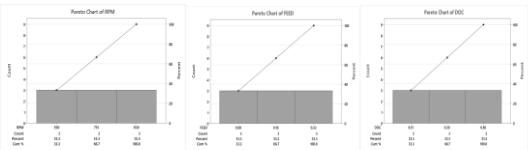

Fig. 5 Pareto analysis for RPM, Feed & DOC

CONCLUSIONS

A comprehensive comparative analysis of the machining characteristics of Mild Steel, a material with lower hardness and ductility and EN24 known for its hardness and strength, under sustainable machining approaches in wet condition is being provided in this research paper. The research presents an analytical approach to sustainable machining by understanding the combined effects of machining parameters which are RPM, Feed, and Depth of cut on surface roughness and machining time on two different materials, Mild Steel and EN 24. By optimizing key factors using the Taguchi L9 method. In this research, ANOVA analysis has been done on the results and Regression analysis gives predictive equations for both the output responses that fit well with the experimental results. The Taguchi design which is combined with the-smaller-the-better approach and S/N ratio approach, determines the optimal parameter settings for each material. By measuring surface roughness and machining time for Mild Steel and EN24 in a single experimental setup, this research addresses a significant gap in the literature. These findings highlight the potential for integrating ecofriendly practices in conventional manufacturing processes without sacrificing productivity or quality.

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