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Sustainable Machining of EN19 Steel: Efficacy of Eco-Friendly Cooling Fluids and Hybrid Optimization Techniques

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Abstract: The study investigates the efficacy of eco-friendly cooling fluids, specifically vegetable oil and water mixtures, in the machining of EN19 steel, with a focus on enhancing performance metrics while promoting environmental sustainability. Machining parameters, including cutting speed, feed rate, and depth of cut (DOC), were analyzed for their effects on surface roughness, tool temperature, cutting forces, and material removal rate (MRR). The study employed a hybrid optimization approach, integrating Taguchi's orthogonal array (OA) method with grey relational analysis (GRA), to evaluate the effectiveness of these eco-friendly cutting fluids. The analysis revealed that spindle speed significantly influenced the MRR, while the DOC notably affected cutting force and tool temperature. The choice of coolant was found to have a considerable impact on surface roughness. Although the Taguchi method effectively optimized individual machining parameters, GRA provided a more comprehensive evaluation by synthesizing multiple performance metrics into a single index, achieving an accuracy of 80.17%, which surpassed the 72.44% accuracy of the Taguchi method. These findings underscore the potential of GRA to optimize the machining process of EN19 steel, offering substantial improvements in manufacturing efficiency and sustainability. The study highlights the importance of adopting eco-friendly practices in industrial machining, demonstrating that the integration of GRA and Taguchi methods can lead to more sustainable and efficient manufacturing processes.

Keywords: Optimization; Milling parameters; Taguchi analysis; Grey relational analysis (GRA)

1 Introduction

Machining EN19 steel, renowned for its toughness and wear resistance, presents a series of significant challenges in the manufacturing process. This high-performance alloy, commonly used in applications requiring high strength and durability, demands precise machining to achieve optimal results. Traditional cooling fluids have long been employed to manage the heat generated during machining, reducing tool wear and enhancing surface finish. However, these conventional fluids are not without their drawbacks. Their chemical compositions and disposal requirements pose considerable environmental risks, which has led to a growing interest in alternative, eco-friendly cooling methods that aim to minimize ecological impact while maintaining effective performance.

In response to these environmental concerns, there has been a notable shift towards exploring and implementing sustainable cooling solutions. These eco-friendly alternatives seek to reduce the negative effects associated with traditional cooling fluids, such as pollution and resource depletion, without compromising the quality and efficiency of the machining process. Alongside the pursuit of environmentally friendly cooling methods, optimizing machining parameters has become a critical focus. Efficient parameter optimization not only improves the overall productivity of the machining process but also enhances the quality of the final product.

To address these challenges, hybrid optimization techniques have emerged as a promising approach. Among these, the GRA method has demonstrated significant potential in multi-objective optimization scenarios. This method integrates various optimization criteria to balance multiple objectives, such as minimizing tool wear, controlling cutting temperatures, and improving surface finish. By leveraging hybrid techniques, manufacturers can achieve a more comprehensive and effective optimization of their machining processes. This paper explores the application of eco-friendly cooling fluids and hybrid optimization methods in the context of machining EN19 steel. The aim is to enhance both sustainability and efficiency in manufacturing processes, aligning with contemporary goals of reducing environmental impact while maintaining high performance standards.

A thorough literature review provides insights into various cooling techniques, each with its own set of advantages and limitations. Singh et al. [1] reviewed sustainable dry cutting, a method where machining is performed without any cooling lubricants, is valued for its simplicity and cost-effectiveness. This approach eliminates the need for additional cooling fluids, reducing associated disposal issues and costs. However, dry cutting presents significant challenges, primarily due to the rapid wear of tools and the high temperatures generated at the cutting zone. The absence of lubrication results in increased friction, which accelerates tool degradation and affects the quality of the machined surface.

Cryogenic machining [2, 3], involves the use of cryogenic coolants, such as liquid nitrogen, to cool the cutting tool and workpiece. This technique is highly effective in mitigating tool wear and managing cutting temperatures due to the extremely low temperatures of cryogenic fluids. Despite its advantages, cryogenic machining is often limited by its high operational costs and the requirement for specialized equipment. Hadad and Sadeghi [4] have pointed out that the expense associated with cryogenic fluids can be prohibitive, making this technique less accessible for some applications.

Minimum Quantity Lubrication (MQL) is another technique that has garnered attention for its potential to balance performance with environmental considerations. According to Bai et al. [5], MQL involves applying a minimal amount of lubricant in the form of an aerosol mist directly to the cutting zone. This method significantly reduces the environmental impact compared to traditional flood cooling methods by minimizing lubricant usage. MQL provides satisfactory cooling and lubrication, and its performance can be further enhanced when combined with advanced substances such as nanofluids or cold air. Air cooling, reviewed by Sultana et al. [6], uses compressed air to manage heat in the cutting zone. While air cooling is less effective than liquid coolants in controlling high temperatures, it offers a simpler and more environmentally friendly alternative. This method is particularly suited for applications with lower cutting temperatures and stringent environmental regulations, providing a feasible solution for situations where traditional cooling methods are not ideal.

Nanofluids, which are suspensions of nanoparticles within base fluids, represent a promising advancement in cooling technology. As highlighted by Ben Bacha et al. [7], nanofluids enhance the thermal conductivity and heat transfer properties of the base fluid, offering superior cooling performance. When used in conjunction with MQL systems, nanofluids can significantly reduce tool wear and improve surface finish, making them an attractive option for high-precision machining applications. Vegetable oils, investigated by Khunt et al. [8], are another environmentally friendly alternative to conventional mineral- and chemical-based coolants. These oils are biodegradable and present a sustainable option for machining processes. They have been found to perform effectively, providing good lubrication and cooling properties.

When used with MQL systems, vegetable oils can help lower cutting temperatures and reduce tool wear, offering both performance and sustainability benefits. Gul et al. [9] investigated the multi-objective optimization of process parameters for industrial gas turbines using Grey-Taguchi and GRA methods, aiming to enhance performance when fueled with natural gas. Their study focused on optimizing key parameters to achieve better efficiency and reduced emissions. Jadhav and Sahai [10] explored sustainable machining of AISI4140 steel using a Taguchi-ANN approach, emphasizing eco-friendly cutting parameters. Their work contributes to understanding the impact of sustainable practices on machining performance and environmental impact.

Ang Kui et al. [11] reviewed the evolution of coolant usage in conventional machining methods, emphasizing advancements in eco-friendly coolants and their effects on machining efficiency and tool life. The study highlights the increasing importance of sustainable practices in manufacturing, addressing both environmental and operational challenges in machining. Li et al. [12] presented empirical models to optimize tool life, residual stress, and surface roughness in titanium alloy milling. Using NSGA-II, the study balances production efficiency and surface quality, achieving Pareto-optimal solutions with minimal errors. The findings provide valuable guidelines for industrial applications. Derani and Ratnam [13] critically reviewed the effectiveness of vegetable oils as cutting fluids in turning operations, focusing on tool wear and surface roughness.

The paper concludes that, while vegetable oils offer significant environmental advantages, their performance varies with machining conditions, necessitating further optimization for consistent results. Onuoha et al. [14] examined the impact of cutting fluids on surface roughness in turning AISI 1330 alloy steel using Taguchi method and identified that the feed rate as the most influential factor, with groundnut oil-based cutting fluid optimizing surface finish. Ogbonna et al. [15] applied the Grey-based Taguchi method to optimize the multi-weld quality in gas metal arc dissimilar joining of mild steel and 316 stainless steels. The study identifies optimal welding parameters, demonstrating the method's effectiveness in improving weld quality across multiple performance metrics.

Table 1. Comparison of cooling techniques and research gaps in machining EN19 steel

Cooling Technique	Description	Advantages	Limitations	Research Gaps	References
Dry Cutting	Machining without any cooling lubricants.	Simplicity; Cost- effectiveness.	Rapid tool wear; High cutting temperatures.	Further research is needed to optimize dry cutting conditions for tough materials like EN19 steel, especially in high-performance applications where precision and durability are crucial.	Singh et al. [1]; Jachav and Sahai [10]
Cryogenic Machining	Uses cryogenic coolants like liquid nitrogen to cool the cutting tool and workpiece.	Significantly reduces tool wear; Effective in managing cutting temperatures.	High operational costs; Requires specialized equipment.	The high cost and limited accessibility of cryogenic machining need to be addressed, particularly for widespread industrial adoption in machining tough alloys like EN19 steel.	Hadad and Sadeghi [4]
MQL	Applies a minimal amount of lubricant as an aerosol mist to the cutting zone.	Reduces environmental impact compared to flood cooling: Satisfactory cooling and lubrication.	Performance may vary based on the lubricant used; May not be as effective in extreme conditions.	There is a need for more comprehensive studies to optimize MQL systems, especially when used with advanced substances like nanofluids, to enhance their effectiveness in machining EN19 gteel	Bai et al. [5]; Ang Kui et al. [11]
Air Cooling	Uses compressed air to dissipate heat from the cutting zone.	Simple and eco- friendly; Suitable for applications with lower cutting temperatures.	Less effective in managing high temperatures compared to liquid coolants.	Research should explore how air cooling can be optimized for specific applications in machining tough materials like EN19 steel, where traditional cooling methods are impractical or less effective.	Sultana et al. [6]
Nanofluids	Suspensions of nanoparticles in base fluids to enhance thermal conductivity and heat transfer.	Superior cooling performance; Reduces tool wear and improves gurface finish.	Can be costly, Performance depends on the type of nanoparticles and base fluids.	More research is needed to evaluate the application of nanofluids with MQL systems in the machining of EN19 steel, focusing on high-precision applications where effective heat management and tool wear reduction are critical.	Ben Bacha et al. [7]; Onuoha et al. [14]
Vegetable Oils	Biodegradable oils used as an altemative to mineral-and chemical-based coolants.	Environmentally friendly; Effective lubrication and cooling; Suatainable.	Performance can vary; May require additional considerations for disposal and application.	Existing research on the application of vegetable oils in machining tough alloys like EN19 steel is limited. This study aims to address these gaps, focusing on their effectiveness in reducing tool wear and improving surface finish while maintaining gustainability.	Khunt et al. [8]; Ang Kui et al. [11]

Okokpujie et al. [16] investigated the multi-objective optimization of machining factors using MWCNTs nano-lubricant in end-milling. The study highlights significant improvements in surface roughness, MRR, and cutting force, showcasing the potential of nano-lubricants to enhance machining efficiency and product quality. Solanke and Gaval [17] applied the Taguchi method to optimize wear parameters for Titanium grades 2 and 5 in orthopedic implants, which significantly improved the durability and performance. Zhang and Rao [18] demonstrated how the Taguchi method enhances machining parameters to improve surface roughness, underscoring its effectiveness in industrial applications. Xavior and Adithan [19] explored how different cutting fluids affect tool wear and surface roughness in turning AISI 304 stainless steel, revealing significant impacts on machining performance. Korkmaz et al. [20] reviewed green cooling and lubrication strategies in metal cutting, emphasizing their role in promoting sustainability and outlining future challenges.

In conclusion, selecting the appropriate cooling technique is crucial for improving tool life, surface finish, and overall machining efficiency. While dry cutting and cryogenic machining each have their own distinct advantages, they also come with limitations. On the other hand, MQL systems—particularly those incorporating nanofluids and vegetable oils—offer a promising balance between high performance and environmental sustainability. Future research should focus on optimizing these eco-friendly cooling methods further and exploring new materials and techniques to enhance their effectiveness. Manufacturers and practitioners should carefully consider the specific requirements of their machining operations and choose cooling techniques that provide the best combination of performance, cost-effectiveness, and minimal environmental impact. Table 1 provides a concise summary of each cooling technique, including its description, advantages, limitations, and relevant references.

2 Methodology

2.1 Test Method

EN19, also recognized as 708M40 in the BS 970 standard, is a high-quality alloy steel for general mechanical and engineering purposes. EN19 steel is characterized by its 1% chromium and molybdenum content. It is also regarded as an equivalent steel grade to 42CrMo4 steel in the EN standard or 4140 steel in the ASTM standard. EN19 steel material is known for its excellent combination of toughness, strength, and wear resistance. It is widely used to make components for machinery, automotive parts, gears, shafts, axles, and other applications. EN19 steel workpieces measuring 100 mm×100 mm×20 mm were subjected to milling operations to evaluate the effects of varying machining parameters on performance outcomes. The experiments were conducted using a milling machine, where spindle speeds were adjusted to 355, 500, and 710 revolutions per minute (rpm) and DOC were set at 0.5, 1, and 1.5 mm. To investigate the influence of cutting fluids, three conditions were tested: the use of neem oil enhanced with graphene oxide (GO) nanoparticles, a conventional machining coolant, and a dry machining condition without any coolant. Dispersion of graphene in neem oil is achieved by sonication process. The high-frequency vibrations break down graphene agglomerates, dispersing the nanosheets evenly throughout the oil. Sonication typically lasts for 45 minutes. The concentration of graphene in the neem oil is carefully controlled to 0.3% by weight. After sonication, the fluid is homogenized to ensure a uniform distribution of graphene particles throughout the cutting fluid.

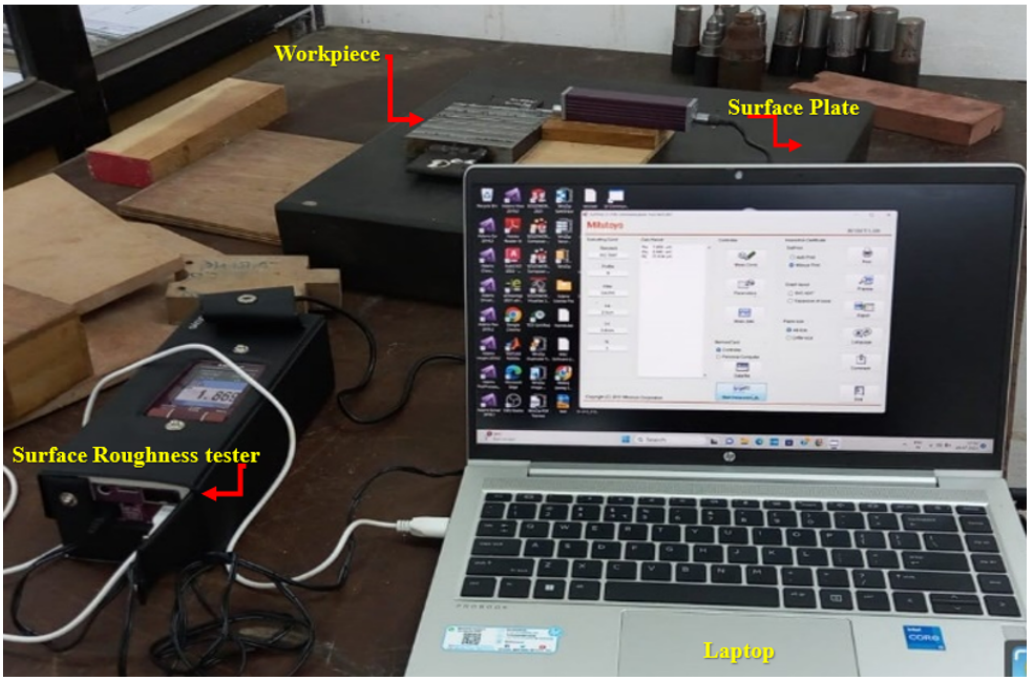


Figure 1. Surface roughness measurement of experimental workpiece

The performance of the milling process was assessed using four key metrics: surface roughness, temperature, MRR, and cutting forces. Surface roughness was measured post-machining to evaluate the quality of the machined surface. A laser infrared thermometer was utilized to record the temperature generated during machining, providing insights into the thermal aspects of the process. Additionally, cutting forces were monitored using an IEICOS Milling Tool Dynamometer, which was strategically mounted on the machine table along with a self-cantering vice (3") to securely hold the workpiece. The dynamometer, equipped with sensors measuring forces in three orthogonal directions, displayed real-time force data on a digital unit, ensuring precise and reliable measurements throughout the experiment. The MRR was calculated using Eq. (1):

$$MMR = DOC * \textit{ the width of cut } * \textit{ the feed per tooth} \tag{1}$$

The surface roughness measurement of the experimental workpiece using the Mitutoyo Surface Roughness Tester is depicted in Figure 1.

3 Taguchi and Design of Experiments (DOE)

3.1 Taguchi Method

The DOE is a structured approach used to understand how different factors influence a particular outcome or response. Essentially, DOE helps in systematically testing various scenarios to determine how changes in one or more factors affect the results. In this study, we used Taguchi's OA method, specifically a 9-experiment array. This approach allows us to test three different parameters, each at three levels, efficiently and effectively. Here is a simple breakdown:

1. Taguchi's Array: We chose a Taguchi array with 9 experiments, which means we performed 9 different tests. Each test varied three parameters, and each parameter was tested at three different levels.

2. Quality Parameters: For each test, we measured three key quality indicators to assess performance.

3. Signal-to-Noise Ratio (SNR) Analysis: To determine the best settings for these parameters, we used SNR analysis. This method helps us find the optimal conditions by evaluating the results of our tests.

4. Data Analysis: The experimental data were analyzed using MINITAB 17, a software tool for statistical analysis. We converted the raw data into SNR to evaluate the effectiveness of each combination of parameters.

In simpler terms, the DOE process involved conducting a series of controlled experiments to explore how different settings affect our quality metrics. By analyzing these results with the help of software, we could determine which settings produced the best outcomes. This approach ensures that we identify the most effective conditions for optimizing our machining process.

Table 2. Features and their levels

Sr. No.	Input Strictures	Levels		
1.	Spindle Speed	355	500	710
2.	DOC	0.5	1	1.5
3.	Coolant Type	Dry (1)	Normal coolant (2)	Neem oil with graphene (3)

Table 3. Taguchi's L9 OA design

Sr. No.	Speed (rpm)	DOC (mm)	Cutting Fluid	Surface Roughness (Ra)	SNR Ra	Temp. °C	SNR Temp.	Cutting Force (N)	SNR Cutting Force
1	355	0.5	1	2.9	-9.2480	30.5	-29.6860	154.88	-43.7999
2	355	1	2	3.3	-10.3703	34.3	-30.7059	217.12	-46.7340
3	355	1.5	3	4.8	-13.6248	46.9	-33.4235	330.82	-50.3918
4	500	0.5	2	2.9	-9.2480	32.1	-30.1301	158.4	-43.9951
5	500	1	3	3.2	-10.1030	39.1	-31.8435	210.01	-46.4448
6	500	1.5	1	2.3	-7.2346	38.7	-31.7542	537.92	-54.6144
7	710	0.5	3	1.9	-5.5751	33.2	-30.4228	72.26	-37.1780
8	710	1	1	4.8	-13.6248	35.1	-30.9061	109.2	-40.7645
9	710	1.5	2	3.1	-9.8272	42.3	-32.5268	218.95	-46.8069

3.2 Progression Strictures Stages

The investigational proposal was implemented using the concepts of DOE and Taguchi scrutiny. Table 2 outlines the criteria that were taken into account for the research, along with their respective levels. The array is shown in

Table 3, providing the arrangement for a series of 9 trials. These arrays are intentionally intended to thoroughly explore the range of parameters, enabling a thorough examination of the variables being studied.

Table 3 and Table 4 present the outcomes of the uncertainty analysis for measurements of surface roughness, temperature, cutting force, and MRR. The measurements include speed (rpm), DOC (mm), cutting fluid, surface roughness (Ra in µm), SNR for surface roughness (SNR Ra), temperature (°C), S/N for temperature (SNR temperature), cutting force (N), and SNR for cutting force (SNR cutting force).

Table 4. Experimental results for MRR

Sr. No.	Speed (rpm)	DOC (mm)	Cutting Fluid	MRR $(\mathrm{mm}^3/\mathrm{s})$	SNR MRR
1	355	0.5	1	2.84	9.0664
2	355	1	2	4	12.0412
3	355	1.5	3	5.68	15.0870
4	500	0.5	2	5.68	15.0870
5	500	1	3	8	18.0618
6	500	1.5	1	11.36	21.1076
7	710	0.5	3	8.52	18.6088
8	710	1	1	12	21.5836
9	710	1.5	2	17.04	24.6294

3.3 Method (Grey-Based Taguchi)

GRA is a technique used to improve multiple aspects of a process by combining various performance measures into a single score. Unlike the traditional Taguchi method, which focuses on optimizing just one performance measure at a time, GRA takes a more holistic approach. Here's how it works in simpler terms:

1 Combining Performance Measures: GRA brings together different performance characteristics (like surface roughness, temperature, and cutting force) into one overall score, called the Grey-Relational Grade (GRG). This helps us see how well the process performs across multiple areas simultaneously.

2 Process Steps:

• Choosing an Array: First, we select an OA, a structured way of organizing experiments.

• Conducting Experiments: Next, we run a series of experiments based on this array.

• Normalizing Data: We then adjust the experimental data so that it's comparable.

• Identifying Performance Factors: We analyze which factors influence performance the most.

• Calculating Scores: We calculate a grey-relational coefficient for each set of data to determine how close the results are to the ideal conditions.

• Ranking and Confirming: Finally, we rank the different settings based on their grey-relational scores and identify the best performing settings.

In essence, GRA helps in understanding how different factors affect overall process performance and finds the best combination of settings for optimal results. This approach provides a more comprehensive evaluation compared to methods that focus on a single performance measure.

3.4 Proposed Hybrid Approach

This paper proposes a hybrid approach using the Taguchi technique and GRA, known as the Taguchi approach based on Grey. The method is applied to parameter optimization after determining the SNRs of output response values. GRA, suitable for multi-response optimization, is used in conjunction with experimental data [9]. Following the collection of experimental data outlined in Table 4, the grey-based Taguchi method was employed for parameter optimization. GRA, well-suited for multi-response optimization, was utilized.

The option that most closely resembles a grade of one is selected. Table 5 presents the results of the investigation, including the deviation sequence, the optimal solutions for positive and negative separation measures, and the corresponding ranks for each experimental run. Table 4 indicates that, among the nine trials, experimental run number 7 has the highest relative Grade value (0.8017). The outcome of this specific experimental run, which has a greater level of quality, indicates that it is approaching the ideal values for the specified criteria. However, it is crucial to generate and consider the average answers, as shown in Table 6, to validate the optimal values. The most effective combination of milling settings may be determined by assessing the average responses. Applying the GRA approach, the optimal arrangement in this case is 7-1-9-4-2-8-6-5-3. This combination of elements is the most optimal approach to achieving the desired outcomes in the milling process, ensuring a comprehensive and reliable optimization methodology.

Table 5. Evaluated relative closeness (Ci) and rank of GRA

Sr. No.	Deviation Sequence				Grey Relational Coefficient - GRC				GRADE	Rank
	Surf. Rough	Temp.	MRR	Cutting Force	Surf. Rough	Temp.	MRR	Cutting Force		
1	0.3448	0.0000	1.0000	0.1774	0.5918	1.0000	0.3333	0.7381	0.7425	2
2	0.4828	0.2317	0.9183	0.3111	0.5088	0.6833	0.3525	0.6165	0.6181	5
3	1.0000	1.0000	0.8000	0.5553	0.3333	0.3333	0.3846	0.4738	0.4775	9
4	0.3448	0.0976	0.8000	0.1850	0.5918	0.8367	0.3846	0.7299	0.6358	4
5	0.4483	0.5244	0.6366	0.2958	0.5273	0.4881	0.4399	0.6283	0.5209	8
6	0.1379	0.5000	0.4000	1.0000	0.7838	0.5000	0.5556	0.3333	0.5432	7
7	0.0000	0.1646	0.6000	0.0000	1.0000	0.7523	0.4545	1.0000	0.8017	1
8	1.0000	0.2805	0.3549	0.0793	0.3333	0.6406	0.5848	0.8631	0.6055	6
9	0.4138	0.7195	0.0000	0.3150	0.5472	0.4100	1.0000	0.6135	0.6427	3

Table 6. Mean response for GRA

Level	Spindle Speed (A)	DOC (B)	Cutting Fluid (C)
1	0.6127	0.7266*	0.6304
2	0.5666	0.5813	0.6322*
3	0.6833*	0.6322	0.6001
Max-Min	-0.0706	0.1721	0.0304
Rank	**2**	**3**	**1**

The mean response of Table 5 confirms that the 7th experiment gives the optimal milling parameters for achieving better machining performances in EN19 steel. The grade values for each experimental number are displayed in Figure 2.

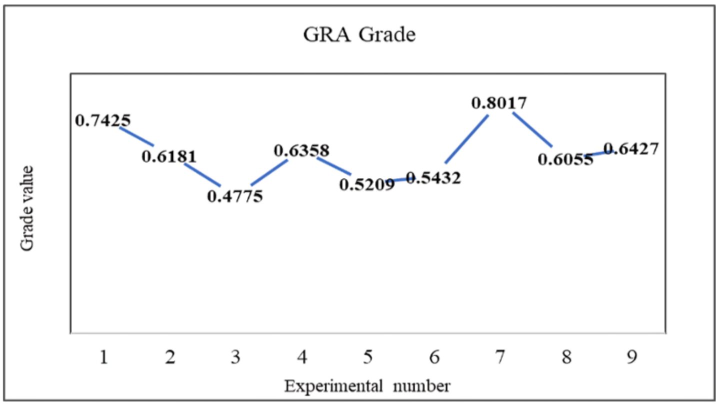


Figure 2. Variation of GRA grade values and experimental number

4 Results

The main objective is to determine the characteristics and interactions that have a substantial influence on surface roughness. To accomplish this goal, the trials are constructed in a methodical GRA utilizing the OA approach. The goal is to understand the link between spindle speed, DOC, coolant type, and surface roughness, finally determining the ideal settings for minimizing surface roughness.

4.1 Influence on Surface Roughness

The study focuses on identifying the key factors affecting surface roughness during machining. Using the GRA approach with an OA, the research examines the relationship between spindle speed, DOC, and coolant type on surface roughness. The findings highlight the significant role of the coolant type in improving surface roughness. The analysis of SNRs reveals the optimal conditions for minimizing surface roughness, emphasizing the need for the appropriate selection of coolant type. Figure 3 and Figure 4 illustrate these findings.

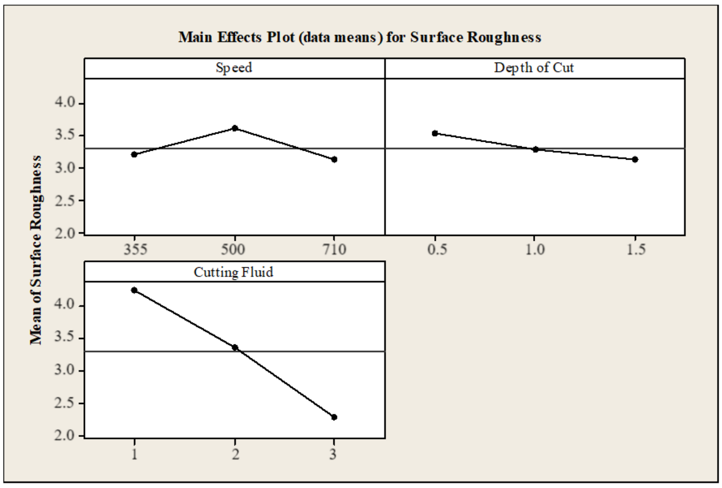


Figure 3. Main effects plot for Ra

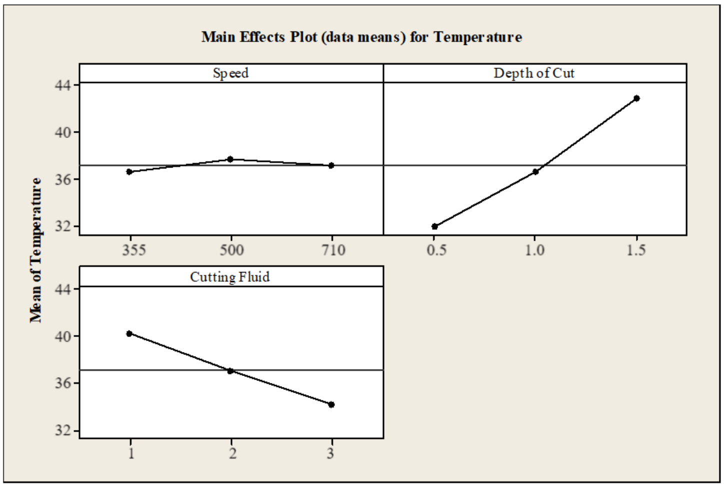


Figure 4. Main effects plot for temperature

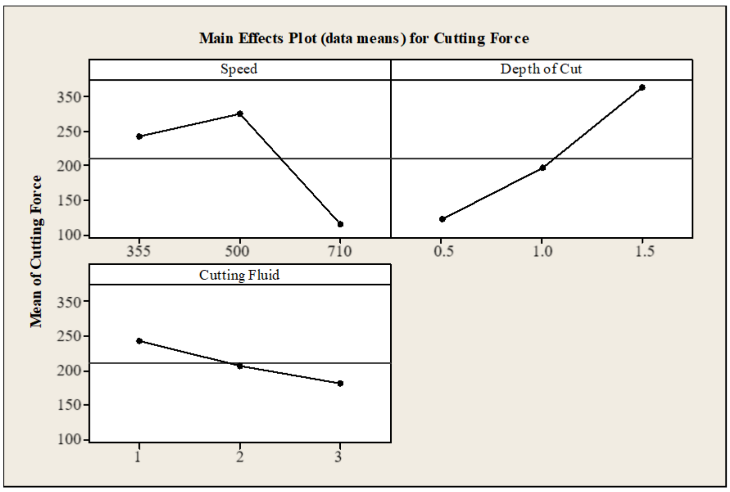


Figure 5. Main effects plot for cutting force

4.2 Influence on Temperature

The research further investigates the impact of machining parameters on temperature. DOC emerges as the most influential factor, followed by coolant type and spindle speed. Statistical analysis using SNRs indicates that controlling the DOC is crucial for managing the thermal aspects of machining. The study identifies optimal parameters for minimizing temperature rise during milling. This is shown in Figure 5 and Figure 6 and is further supported by the data presented in Table 6.

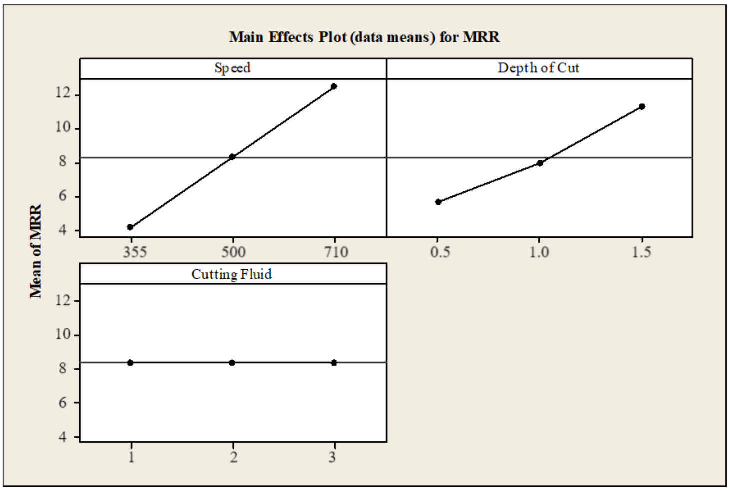


Figure 6. Main effects plot for MRR

4.3 Influence on Cutting Force

Cutting forces during machining are primarily affected by the DOC, with spindle speed and coolant type also playing significant roles. The study demonstrates that DOC is the dominant factor influencing cutting forces, as detailed in Table 7. The SNR analysis presented in Figure 7 and Figure 8 helps identify the ideal conditions for reducing cutting forces, highlighting the importance of controlling the DOC to enhance machining efficiency and tool life.

Table 7. SNR (analysis of variance)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	5.79511	1.93170	4.38	0.073
Spindle speed	1	0.14678	0.14678	0.33	0.589
DOC	1	0.04167	0.04167	0.09	0.771
Coolant type	1	5.60667	5.60667	12.71	0.016
Error	5	2.20489	0.44098		
Total	8	8.00000			

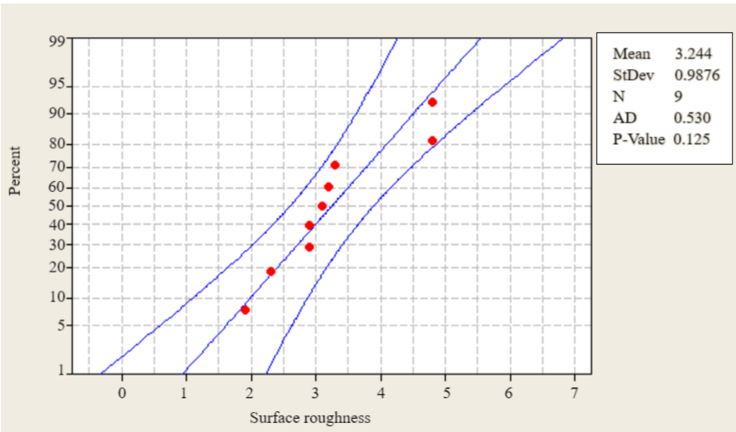
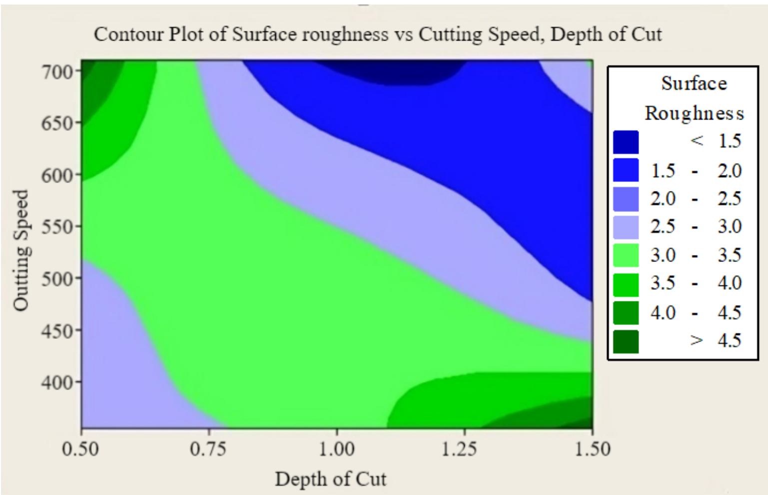
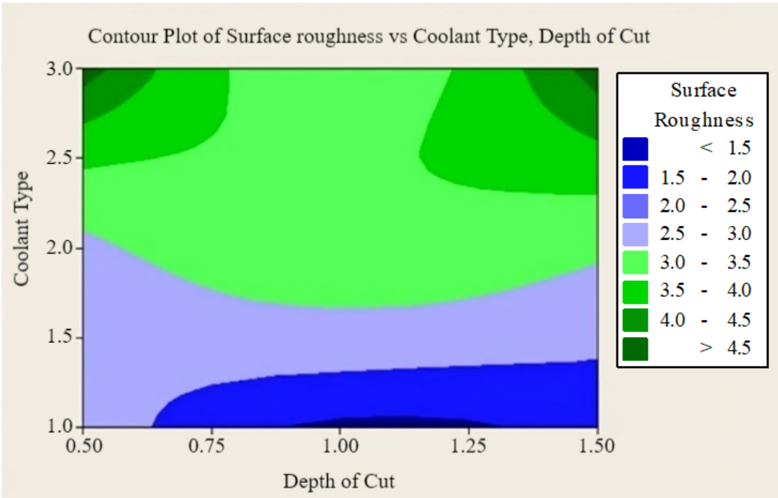


Figure 7. Standard deviation plot of surface roughness



(a)



(b)

Figure 8. Silhouette graph for surface roughness of (a) Cutting speed, DOC; (b) Coolant type, DOC

4.4 Influence on MRR

The study examines the effects of machining parameters on MRR. The analysis reveals that spindle speed has the most significant impact on MRR, followed by DOC, while coolant type has a lesser effect. The SNR analysis helps identify the optimal machining parameters to maximize MRR, with Figure 6 emphasizing the importance of selecting the appropriate spindle speed for increased productivity and efficiency.

4.5 ANOVA for SNR

ANOVA is a technique used to analyze differences in group means in experimental data, aiding in informed decision-making. Table 7 displays ANOVA results, revealing individual contributions to variability in the SNR and their impact on all output parameters.

The type of coolant significantly impacts surface roughness, indicating its importance in achieving higher surface quality. Cutting speed and DOC are secondary factors, with temperature being primarily influenced by the DOC. Temperature regulation is crucial to minimizing temperature increases. Cutting force is primarily influenced by the DOC, with speed and coolant type having secondary effects. A higher spindle speed is essential for optimum material removal. The depth of the cut and type of coolant also play crucial roles. The R-squared value of 72.44% in Table 8 indicates the model's suitability for predicting optimal process parameters. Eq. (2) provides a summary of the optimal conditions obtained by regression analysis.

$$Surface\ Roughness = 1.92 - 0.00088\,Cutting\ speeds - 0.167\,DOC + 0.967\,Coolant\ type \quad (2)$$

Table 8. Prototypical summary

S	R-sq	R-sq(adi)	R-sq(pred)
0.664062	72.44%	55.90%	0.00%

4.6 Consequence on Surface Roughness, Temperature, Force, and MRR Owed to Spindle Speed, DOC, and Type of Coolant

This comprehensive depiction is crucial for understanding the fundamental forces affecting Taguchi analysis results in the environmentally responsible machining of EN19 steel. The study found that the coolant type is the most important.

1. The surface roughness is significantly influenced by the kind of coolant used, the DOC, and the cutting speed. The most favorable circumstances for minimizing surface roughness were identified, emphasizing the significance of the coolant type.

2. Temperature is mostly determined by the DOC; however, coolant type and spindle speed also have a significant impact. The ideal conditions for mitigating temperature rise were determined, highlighting the need to regulate the depth of the incision.

3. Cutting Force: The primary factor influencing cutting force is the DOC, with spindle speed and coolant type being secondary factors. The optimal conditions for reducing cutting pressures were identified, highlighting the need for controlling the DOC.

4. The MRR: The kind of coolant used has a little impact on the MRR. The best parameters for maximizing Material Removal Rate (MRR) were determined, highlighting the importance of appropriate spindle speeds. These comprehensive evaluations provide a precise understanding of the comparative significance of many factors within the framework of environmentally sensible machining.

4.7 Silhouette Graph of Cutting Speeds and Surface Roughness Versus DOC

Silhouette plots visually provide distinct outlines that show predicted variables of reaction. The contour plots in Figure 8 provide a clear depiction of the impact of various process parameters on the surface roughness value. After a thorough analysis of subgraph (a) of Figure 8, it is evident that a higher cutting speed is correlated with a higher external unevenness value. Therefore, it may be inferred that the particular state of the cutting fluid has a substantial influence on minimizing surface roughness when machining. The use of neem oil in conjunction with graphene cutting fluid seems to be a fruitful approach.

5 Discussions

The study provides a comprehensive analysis of the influence of spindle speed, DOC, and coolant type on surface roughness, temperature, cutting force, and MRR during the machining of EN19 steel. The findings reveal that coolant type is crucial for achieving higher surface quality, with surface roughness significantly affected by the choice of coolant, DOC, and spindle speed. The research underscores the importance of controlling the DOC to manage temperature and cutting forces, while spindle speed is identified as a critical factor for optimizing MRR. The ANOVA results presented in Table 6 further validate the significance of these factors, with the R-squared value of 72.44% indicating the model's suitability for predicting optimal process parameters.

The silhouette plots in Figure 8 offer a visual representation of the relationship between cutting speed, DOC, and surface roughness. The analysis suggests that higher cutting speeds are associated with increased surface roughness, while the use of neem oil with graphene-enhanced cutting fluid significantly reduces surface roughness, making it a promising approach for environmentally responsible machining.

6 Model Comparison

The study compares the Taguchi method and GRA for optimizing machining parameters for EN19 steel. It explores how these techniques enhance precision machining procedures by combining cutting parameters with outputs.

6.1 The Taguchi Method

The Taguchi technique, a method based on SNR, is used to analyze the impact of various factors on output responses. In this study, the Taguchi L9 OA was utilized to optimize machining settings, focusing on reducing surface roughness and cutting force while managing temperature and optimizing MRR. Results showed that coolant type significantly affected surface roughness, cutting force and temperature were influenced by cut depth, and spindle speed significantly affected MRR.

6.2 GRA

GRA was utilized to combine several replies into a single grey relational grade, resulting in a complete evaluation of performance across multiple categories. This approach compares the relative performance of various parameter settings by normalizing the experimental data and computing GRCs, which are then combined to generate the grey relational grade. The GRA technique successfully identified the best combination of machining parameters for achieving balanced performance across surface roughness, temperature, cutting force, and MRR.

6.3 Comparison of Results

The Taguchi technique and GRA (Table 8) are compared to show their relative strengths in optimizing machining settings for EN19 steel. While the Taguchi technique provides a simple and reliable framework for finding relevant elements and optimal settings, GRA gives a more sophisticated evaluation by combining many performance measurements into a single index.

The comparison in Table 9 emphasizes the greater performance of the GRA in measuring the overall machining quality, in contrast to the Taguchi approach, which focuses on optimizing individual replies. GRA's incorporation of many performance measures into a unified index highlights its ability to improve accuracy in machining processes, specifically in achieving a balance between surface quality, thermal impacts, cutting pressures, and MRRs while turning EN19 steel.

Table 9. Comparison of Taguchi and GRA method

Model	Statistical Method	Features Considered	Output Variable	Presentation Metric	Accuracy (%)
Taguchi	OA	Spindle speed, DOC, coolant type	Surface roughness, temperature, cutting force, MRR	SNR	72.44
GRA	GRA	Spindle speed, DOC, coolant type	Surface roughness, temperature, cutting force, MRR	Grey Relational Grade	80.17

7 Conclusions

This study successfully optimized the multi-performance characteristics of machining EN19 steel by comparing the Taguchi method and GRA. Several key findings have emerged, offering valuable insights for both researchers and practitioners in the machining industry:

1. Taguchi method: Utilizing the Taguchi L9 OA, the study identified that spindle speed significantly influences MRR, DOC affects cutting force and temperature, and coolant type impacts surface roughness. However, the Taguchi method's focus on individual responses limits its overall optimization capability, as it does not adequately address the interaction between multiple performance metrics.

2. GRA: GRA provided a comprehensive evaluation by combining multiple performance measures into a single index. This method successfully identified the optimal machining parameters for balanced performance across surface roughness, cutting force, temperature, and MRR. The GRA method demonstrated superior accuracy (80.17%) compared to the Taguchi method (72.44%), highlighting its effectiveness in optimizing complex machining processes.

3. Practical implications for the machining industry: The study's findings have significant practical implications for the machining industry, particularly in the adoption of eco-friendly cooling fluids and hybrid optimization techniques. Implementing vegetable oil and water mixtures as cutting fluids offers a sustainable alternative to traditional coolants, reducing environmental impact while maintaining or even enhancing machining performance. The use of GRA as an optimization tool allows manufacturers to achieve a balanced approach, improving surface quality, reducing tool wear, and optimizing MRRs. However, the transition to eco-friendly coolants may face challenges such as the need for equipment adaptation, higher initial costs, and potential variability in performance based on specific machining conditions.

4. Challenges and opportunities: While the implementation of eco-friendly cooling fluids and hybrid optimization techniques presents opportunities for sustainable manufacturing, challenges remain. The effectiveness of vegetable oil-based coolants may vary depending on the machining environment, and further research is needed to standardize their use across different applications. Additionally, the integration of advanced optimization techniques like GRA requires a deeper understanding of the interactions between various machining parameters, which may necessitate additional training and resources for industry professionals.

5. Future research directions: Building upon this study, future research could explore the long-term effects of eco-friendly coolants on tool life and overall machining efficiency. Investigating the potential for combining GRA with other optimization methods, such as artificial intelligence or machine learning, could further enhance the accuracy

and applicability of these techniques in real-world settings. Additionally, expanding the scope of research to include other materials and machining processes would provide a broader understanding of the benefits and limitations of these sustainable approaches.

In conclusion, this study underscores the importance of using advanced optimization techniques like GRA to achieve a balanced and efficient machining process, particularly when multiple performance characteristics must be considered simultaneously. The findings contribute to the ongoing efforts to enhance sustainability and efficiency in manufacturing, offering a pathway for the machining industry to adopt more environmentally responsible practices without compromising on performance.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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