Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 11, Special Issue 12, 2023
DOI (Journal): 10.37591/JoPC

http://engineeringjournals.stmjournals.in/index.php/JoPC/index

Research JoPC

Performance Evaluation of Eco-friendly Cutting Fluid in Machining Process—An Approach towards Environmentally Friendly Production

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Abstract

The machining industry's evolving environmental consciousness has prompted a growing demand for cutting fluids devoid of chlorine and sulphur, thus fostering sustainable machining practices. This surge in demand is driven by mounting apprehensions over environmental contamination and worker safety. As the industry transitions to modern cutting fluids, it becomes imperative to comprehend their effectiveness and the optimal machine parameters required for their deployment in the turning process. In our current study, we employ the Taguchi technique in conjunction with Grey Relational Analysis (GRA) to assess the efficacy of parameter optimization and its impact on the turning of SS 304 steel, utilizing non-toxic, biodegradable vegetable-based cutting fluids. Our investigation delves into the influence of various process variables, including cooling conditions (CC), cutting speed (Vc), feed rate (f), and depth of cut (a), on critical response parameters like Cutting Force (CF) and Surface Roughness (SR). This is accomplished through rigorous Analysis of Variance (ANOVA) to identify the parameters of significant influence. The study reveals that employing the Minimum Quantity Lubrication (MQL) method at a cutting speed of 1000 revolutions per minute, a feed rate of 90 mm/minute, and a 0.3 depth of cut leads to substantial enhancements in machining performance. The microstructure of the optimized sample is investigated through the use of a Scanning Electron Microscope. Optimally, MQL machining at Vc 1000 rpm, f 90 mm/min, and a 0.3 mm minimized CF. Additionally, the type of cutting coolant (CC), a, Vc, and f contributed 77.77%, 6.54%, 4.606%, and 2.328%, respectively, to CF reduction.

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Received Date: October 30, 2023
Accepted Date: January 05, 2024
Published Date: April 01, 2024

Citation: Javvadi Eswara Manikanta, B. Naga Raju, Chitrada Prasad, Naveen Kumar Gurajala, N Malleswararao Battina. Performance Evaluation of Eco-friendly Cutting Fluid in Machining Process—An Approach towards Environmentally Friendly Production. Journal of Polymer & Composites. 2023; 11(Special Issue 13): S149–S160.

Keywords: Eco friendly cutting fluids, Turning, Minimum Quantity Lubrication (MQL), Surface roughness, cutting force, Optimization.

INTRODUCTION

Stainless steel possesses a variety of industrial applications. This results from its exceptional corrosion resistance quality [1, 2]. Yet, it has poor thermal conductivity and a significant potential to work harden. Excessive tool wear is a prevalent issue, which results in a poor surface finish for the machined work item [3, 4]. This material has low thermal conductivity, resulting in an aggressive cutting environment and the growth of highly high cutting temperatures. The machining process needs cutting fluids and optimal input parameters to enhance machining characteristics by reducing heat [5, 6]. In the current scenario, manufacturing industries require more eco-friendly cutting fluids. Therefore, researchers around the globe focus on developing new cutting fluids that would improve the quality of machining products [7, 8]. This need for new green cutting fluids has led to the use of biodegradable oils from trees, plants, and seeds [9]. Therefore, it has recently become one of the most widely investigated research topics [10]. To be classed as primary processing, machined workpieces must meet a specific level of precision, and the parameters are frequently selected to operate the equipment properly. While this process often produces the desired properties, it may not be suitable for mass production [11, 12]. Surface roughness is a sign of final product excellence in the manufacturing sector. The roughness standard deviation is a crucial measure of the cutting surface completeness. The resulting surface roughness must be within permissible limits, which are determined by the settings and the skills of the individual operator creating them [13]. The cutting force is also another important indicator of processing quality. Cutting forces cause premature tool wear and degrade product surface quality.

As a result, the process variables and their levels that produce the least cutting force and surface roughness must be chosen [14]. The overall cost of such a machining process must be considered [15]. Design is critical to obtaining optimal machining parameters, and the well-known Taguchi optimization technique was used to investigate and determine the most effective parameter combinations [16]. The Taguchi approach employs an orthogonal table containing experimental control parameters, which significantly decreases operation time and cost [17–20]. Pang et al. [21] the grey fuzzy algorithm and Taguchi technique were used to optimize material processing factors. Das et al. [22, 23] utilized the same methods to determine the best machining condition. Gupta et al. [24] investigated parameter optimization for AISI steel materials using Taguchi and fuzzy techniques. Asil Turk et al. [25] used Taguchi and RSM to study surface irregularities. Li et al. [26] utilized parameter correlation, RSM, and multi-objective swarm optimization in the Taguchi technique to investigate optimal. Daniel et al. [27] employed an ANN to forecast and optimize Taguchi using GRA to assess milling operation. Thankachan et al. [28] employed the Taguchi technique, grey relational analysis (GRA), and an ANN to forecast and optimize surface roughness. Tamiloli et al. [29] analyzed GRA utilizing Taguchi experimental tests and generated a neuro-fuzzy system to select input parameters. It shows that the signal-to-noise ratio(S/N) produced from Taguchi investigations may be used for relational GRA analysis. The Taguchi technique is primarily used to decrease the number of tests, and grey relations offer successful outcomes for accounting in small progressions. Padmini et al. [30] tested the turning of AISI 1040 steel by scattering molybdenum disulfide nanoparticles in various vegetable oils and applying them to the machining zone. This study uses Taguchi-based grey Relational Evaluation to perform multi-objective optimization. Murat et al. [31, 32]created a design of experiments to investigate the impact of key turning factors based on the mean roughness and average maximum height of the profile while turning steel. The experiments used dry cutting, standard wet cooling, and MQL. The influence of cutting variables on Ra and Rz was investigated using ANOVA. The statistical software MINITAB 19 was used for designing experiments. 3D surface graphs, S/N ratios, and significant effect graphs were used to analyze the data. Bo-Lin et al. [33] utilized the Taguchi with GRA in a realistic analysis of precision lathe processing. It reveals that, in metal cutting, cutting accuracy is mostly influenced by the depth of cut, spindle speed, Surface roughness, and material removal rate.

Prahlada et al. [34] utilized response surface methods to estimate Surface roughness (SR) and Cutting force (CF) during the MQL turning of AISI 4340 with nanofluid. It was determined that the depth of cut has the most significant impact on cutting force factors concerning the feed rate and cutting speed. An effort to determine the best possible set of process variables utilizing GRA multi-objective optimization to obtain the lowest possible CF and SR when using vegetable-based green cutting fluid. The statistically significant input parameters affecting the output responses were found using analysis of variance (ANOVA). The machined workpiece with the ideal set of Process parameters has been used for the microstructural analysis. In conclusion, research in machining processes, especially with stainless steel, emphasizes optimization techniques like Taguchi and GRA to enhance quality and efficiency while considering eco-friendly cutting fluid. Figure 1. Shows the Graphical representation of workflow.

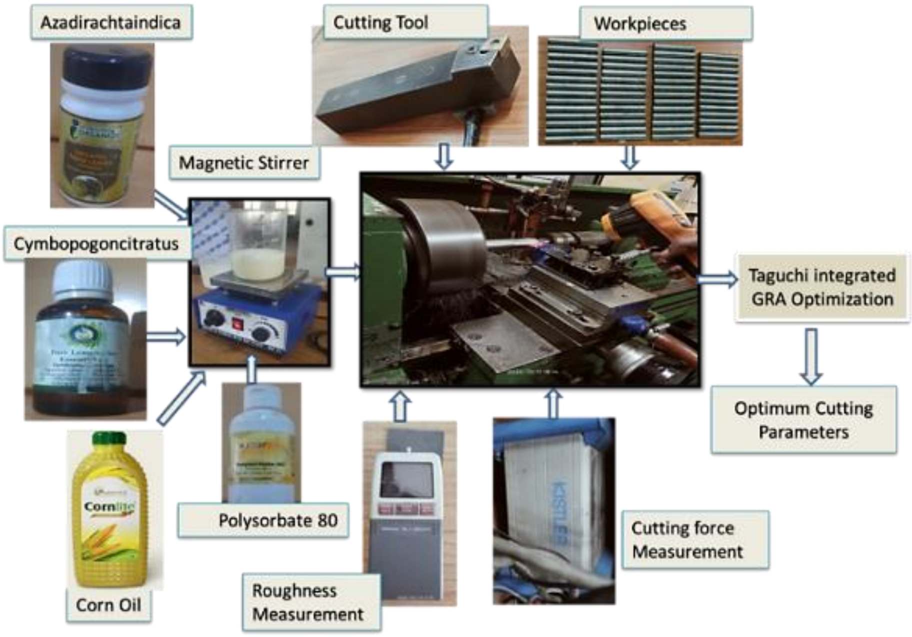

Figure 1. Graphical representation of workflow.

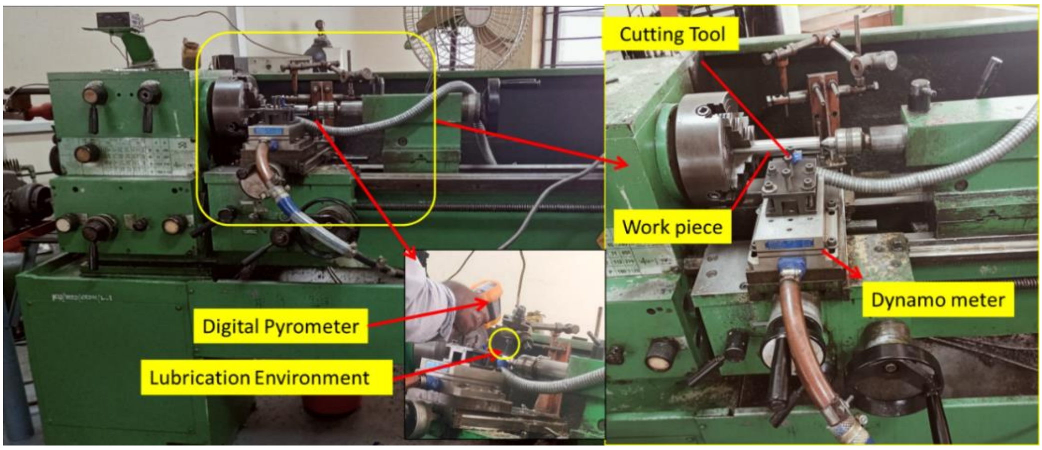

Figure 2. Centre lathe machine (Make: Kirloskar).

Table 1. Chemical elements in SS 304.

Element	Cr	Ni	Mn	N	Si	C	P	S	Fe
Wt.%	18.1	9.4	2	0.9	0.14	0.07	0.05	0.03	69.31

EXPERIMENTATION

Materials and Tool Specifications

In this research, Experiments were conducted on the center lathe machine shown in Figure 2. The quantification of chemical elements in workpiece SS 304 is presented in Table 1. The turning tests were done using a center lathe machine and TiAlN PVD coated tool insert specifications, and the machining specifications were given in Table 2. SS 304 was used as a workpiece, shown in Figure 3, with a diameter of 50 mm and length of 200 mm due to its vast application and high hardness. The tool holder is connected to four components of a piezoelectric dynamometer connected to a multichannel charge amplifier (Amplifier Type 5070a with Pressure and Temperature), data acquisition equipment (DynoWare2825D), and a graphical programming environment for data analysis and visualization. Concerning the surface roughness of the workpiece, the roughness measuring instrument moves directly over the machined surface for measurement after each test.

Table 2. Instruments and specifications.

Instrument and made	**Specifications**
Centre lathe machine: (Shown in Figure 2)	Model:turn-master-35, (Make: Kirloskar)
Tool holder: (Shown in Figure 2)	ISO reference: PSBNR 2525M-12(Coated Carbide)
Workpiece: (Shown in Figure 3)	SS 304 alloy 50 mm diameter, 200 mm length
Tool: (Shown in Figure 3)	TiAlN PVD coated tool Make: SU-Sumitomo Model: SNMG 120408 NSU Grade AC510U
Lubricating oil in wet and MQL Environments (Shown in Figure 3)	Corn-based green-cutting oil the flow rate in wet lubrication: 40 l/min the flow rate in MQL: 10 ml/min, Air pressure: 4 bar
piezoelectric dynamometer	Model: Kistler 9257B
Roughness meter Model: Mitutoyo SJ.201P	Diamond tip as probe radius: 5 µm

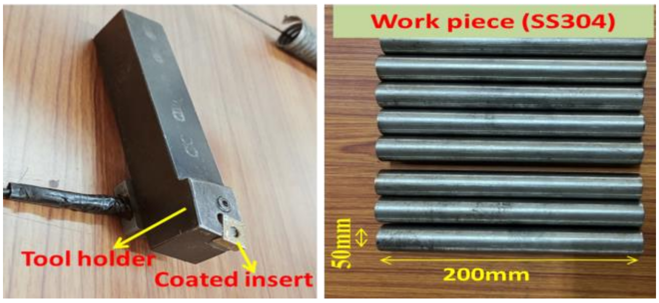

Figure 3. Tool holders, coated insert tool, and workpieces (SS304).

Figure 4. Corn-based green cutting fluid.

Synthesis of Corn-based Green Cutting Fluid

Synthesize Green Cutting Fluid (GCF) by utilizing environmentally friendly, biodegradable base materials, as illustrated in Figure 4. The use of Corn oil as a base oil with the addition of Polysorbate 80, Polysorbate 85, and Triethanolamine for emulsion. The oil is obtained from AzadirachtaIndica, Cymbopogoncitratus. The stems and leaves of CentellaAsiatica were extracted and added to the oil as green additives. To enhance the fluid's anti-toxic properties, we introduce jaggery syrup and turmeric powder into the formulation [35]. The precise quantities of Corn oil, emulsifiers, and additional minerals are detailed in Table 3.

Table 3. Composition of cutting fluid.

S.N.	Additives		Quantity
1	Corn Oil		80%
2	Emulsifier: (100%) Polysorbate 85 Polysorbate 80 Triethanolamine	 77% 20% 3%	10%
3	Additives (100%) Azadirachtaindica Cymbopogoncitratus Centellaasiatica's jaggery syrup turmeric	 10% 30% 30% 20% 10%	10%

Table 4. Machining process parameters

Factors	Units	Levels		
		1	***2***	***3***
Lubrication Environment		Dry	Wet	MQL
Cutting Speed (Vc)	rpm	600	800	1000
Feed (f)	mm/min	30	60	90
Depth of cut (a)	mm	0.3	0.45	0.6

Cutting Conditions and Experimental Design

The experiment conditions and cutting parameters are set according to various aspects such as work material, machine tool, cutting tool, and lubrication methods. The cutting parameters and their levels are shown in Table 4. The tests were carried out under dry, conventional wet cooling (flood cooling), and MQL conditions. Corn-based green cutting oil (CBGC) was used as a coolant for the MQL and Wet cooling methods. In MQL conditions, the cutting fluid flow rate is 10 ml/min pulverized through a nozzle at an air compression pressure of 4 bars. The calculation of four turning parameters, specifically CC, Vc, f, and a, at three different levels, was systematically conducted using the Taguchi L27 orthogonal array, as detailed in Table 5. Furthermore, the resulting response values are also provided. The Taguchi method, employing the L27 orthogonal array, minimizes the requisite number of experiments while ensuring robust statistical analysis. To assess the impact of CC, Vc, f, and a on CF and SR, Analysis of Means (ANOM) and Analysis of Variance (ANOVA) were employed. ANOM prioritizes input factors based on their influence, assigning each element a distinct rank. The primary parameter for gauging the disparity between measured and predicted values is the loss function. This loss function is articulated to the signal-to-noise (S/N) ratio, which quantifies the proportion of the desired signal relative to the undesired random noise that introduces distortion into the output signal. This function encapsulates the qualitative characteristics of diverse observations. Initially, the S/N ratio function is categorized into three distinct types: more minor, more significant, and nominally more efficient. In our current study, the optimization of CF and SR under optimal conditions utilizes a smaller and more efficient signal-to-noise ratio (expressed in dB units). The S/N ratio is computed using Equation 1.

$$\left(\frac{\mathrm{S}}{\mathrm{N}}\right) = -10\log\left(\frac{1}{\mathrm{n_r}}\right)\sum Y_{ij^2} \quad (1)$$

$$\left(\begin{matrix} n = number\ of\ tests\ in\ trail \\ Y_{ij}\ is\ the\ ij\ th\ observation\ of\ the\ quality\ characteristic \end{matrix}\right)$$

RESULTS AND DISCUSSIONS

Machining responses are recorded and statistically analysed to evaluate the characteristics of the lubrication environment and machining parameters

Table 5. Taguchi experimental design test and response values.

Run order	Lubrication Environment	Vc	f	a	CF (N)	CF S/N ratio	SR (μm)	SR S/N ratio
1	Dry	600	30	0.3	176	-44.91	1.37	-2.73
2	Dry	600	60	0.45	168	-44.51	1.31	-2.35
3	Dry	600	90	0.6	164	-44.30	1.22	-1.73
4	Dry	800	30	0.45	163	-44.24	1.29	-2.21
5	Dry	800	60	0.6	167	-44.45	1.34	-2.54
6	Dry	800	90	0.3	165	-44.35	1.32	-2.41
7	Dry	1000	30	0.6	162	-44.19	1.32	-2.41
8	Dry	1000	60	0.3	168	-44.51	1.29	-2.21
9	Dry	1000	90	0.45	161	-44.14	1.25	-1.94
10	Wet	600	30	0.45	154	-43.75	1.26	-2.01
11	Wet	600	60	0.6	152	-43.64	1.20	-1.58
12	Wet	600	90	0.3	157	-43.92	1.23	-1.80
13	Wet	800	30	0.6	151	-43.58	1.16	-1.29
14	Wet	800	60	0.3	156	-43.86	1.14	-1.14
15	Wet	800	90	0.45	162	-44.19	1.02	-0.17
16	Wet	1000	30	0.3	150	-43.52	1.12	-0.98
17	Wet	1000	60	0.45	165	-44.35	0.99	0.09
18	Wet	1000	90	0.6	147	-43.35	1.15	-1.21
19	MQL	600	30	0.6	138	-42.80	1.09	-0.75
20	MQL	600	60	0.3	132	-42.41	1.18	-1.44
21	MQL	600	90	0.45	141	-42.98	1.14	-1.14
22	MQL	800	30	0.3	134	-42.54	0.98	0.18
23	MQL	800	60	0.45	141	-42.98	0.97	0.26
24	MQL	800	90	0.6	156	-43.86	0.93	0.63
25	MQL	1000	30	0.45	132	-42.41	0.90	0.92
26	MQL	1000	60	0.6	128	-42.14	0.94	0.54
27	MQL	1000	90	0.3	124	-41.87	0.93	0.63

Cutting Force (CF)

The experimental investigations reveal that the CF varies within a range of 132 N to 176 N. Figure 5 shows that machining with the MQL method gives the lowest CF compared to dry and wet lubrication systems. Vibrations and friction between the workpiece and tool are the primary responsible parameters for cutting force. A thin layer formation in MQL machining leads to minimum CF.

From the values of experimental results in Table 7, it can be seen that MQL machining with a Vc of 1000 rpm, f of 90 mm/min, and 0.3 mm a gives the lowest cutting forces. Figure 5 shows the factor that affects the elemental cutting force. MQL machining at a Vc of 1000 rpm, (f) of 90 mm/min, and 0.45(a) is the optimal condition for cutting force reduction, provided in Table 6. Input parameters affecting the sequential main force cutting are the type of CC, a, Vc, and f, as shown in Table 8. The contribution of the CC, a, Vc, and f to the reduction in the main cutting force is 77.77%, 6.54%, 4.606%, and 2.328%, respectively, as listed in Table 8.

Surface Roughness (SR)

SR is a quality index parameter. The size of the crater created and the number of debris cracks on the surface closely correlate to the roughness of the character created by machining. SR was measured by a cut-off length of 0.8 mm and five sampling lengths. The experimental investigations reveal that the roughness of the surface varies within a range of 0.90 µm to 1.37 µm. It can be seen from Figure 6 that machining with the MQL method depicts the lowest SR compared to dry and wet lubrication systems.

The MQL method provides an aerosol form of cutting fluid on the exact location of the machining area with high pressure. Due to forced convection and aerosol from thin layer generation in the machining zone provides better lubrication and practical cooling effect resulting in low SR. From Table 5 experimental result values, MQL machining with a Vc of 1000 rev/min, f of 30 mm/min, and 0.45 a gave the most minor surface roughness. Figure 6 conveys the input parameters results on the surface roughness.

MQL machining with a Vc of 1000 rev/min, (f) of 30 mm/min, and 0.3 (a) is the optimum condition for reduction of cutting force from Table 7. The sequence in which input parameters impact the surface roughness is Lubrication Type, Vc, f, and a, as given in Table 9. The extent of each factor's contribution is 59.64% with CC, 14.41% with, followed by f.

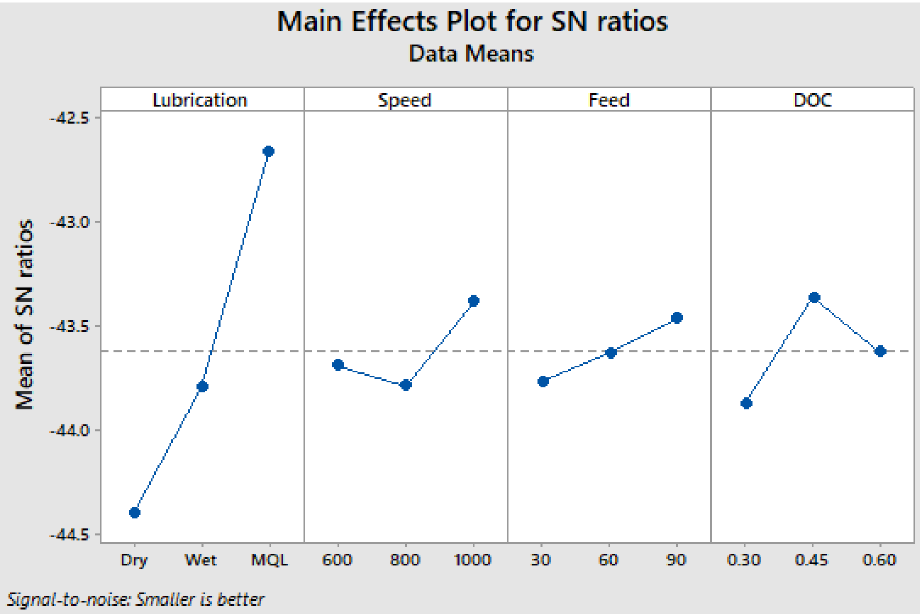

Figure 5. Factors effects on cutting force.

Table 6. ANOM for S/N ratios of CF.

Level	Lubrication	Speed	Feed	DOC
1	-44.40	-43.69	-43.77	-43.87
2	-43.80	-43.79	-43.63	-43.36
3	-42.67	-43.39	-43.46	-43.62
Delta	1.73	0.40	0.30	0.51
Rank	1	3	4	2

Table 7. ANOM for S/N ratios of SR.

Level	Lubrication	Speed	Feed	DOC
1	-2.28154	-1.72449	-1.09661	-1.00339
2	-1.12216	-0.96603	-1.10459	-1.24600
3	-0.01899	-0.73217	-1.22149	-1.17330
Delta	2.26255	0.99232	0.12488	0.24260
Rank	1	2	4	3

Table 8. Analysis of Variance for cutting force S/N ratios.

Source	DF	Seq SS	Adj MS	F	P	% of contribution
Lubrication	2	13.909	6.9546	106.2	0.00	77.77
Speed	2	0.7831	0.3915	5.98	0.03	4.606
Feed	2	0.4165	0.208	3.18	0.11	2.328
DOC	2	1.1705	0.5852	8.94	0.01	6.54
Lubrication* Speed	4	0.8725	0.2181	3.33	0.09	4.87
Lubrication* DOC	4	0.2186	0.0546	0.83	0.55	1.22
Speed*DOC	4	0.1207	0.0301	0.46	0.76	0.67
Residual Error	6	0.3928	0.0654			2.19
Total	26	17.884				100

Table 9. Analysis of Variance for surface roughness S/N ratios.

Source	DF	Seq SS	Adj MS	F	P	% of contribution
Lubrication	2	20.040	11.520	58.2	0.00	59.64
Speed	2	4.8440	2.4220	12.2	0.00	14.41
Feed	2	3.0880	0.0440	0.22	0.00	9.19
DOC	2	1.2790	0.1395	0.70	0.63	3.80
Lubrication* Speed	4	1.8113	0.7028	3.55	0.08	5.39
Lubrication* DOC	4	0.8639	0.2160	1.09	0.43	2.57
Speed*DOC	4	0.4874	0.1219	0.62	0.66	1.44
Residual Error	6	1.1877	0.1980			3.534
Total	26	33.602				100

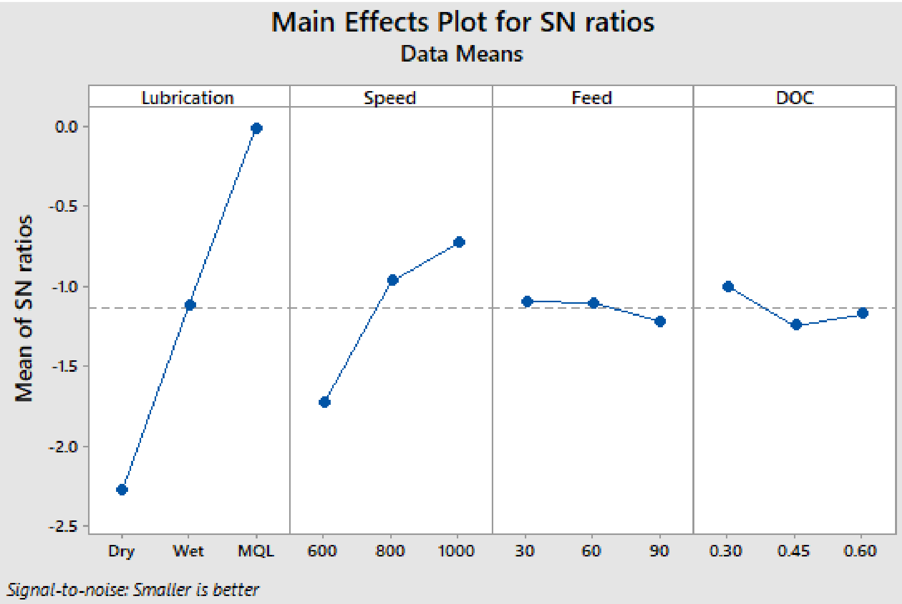

Figure 6. Factors effects on surface roughness.

Process Parameters Optimization Using GRA

The GRA method was used extensively in investigations, including metal cutting experiments, in which optimal test parameters were created to achieve efficient machining efficiency. Taguchi quality is determined by computing S/N and determining which experimental mix of elements is best for specific goals. GRA was performed using sequence data from the Taguchi L27orthogonal array experiment. The intended quality was optimized for many purposes. Table 10 lists the normalized S/N ratios, respective target sequences, and GRA analysis results. It was found that the 27th combination is the (Ranked 1) best for the machining process through GRA. Thus, the seventh combination has beneficial effects for optimizing CF and SR output parameters. The Taguchi quality experimental approach was applied to discover a single optimization target combination related to the preceding variety. GRA was utilized to find the ideal machining conditions. Thus, machine users can select a "single goal" for the best parameters for many output parameters optimizations" with the aid of GRA.

Table 10. Optimized process parameters using GRA.

	S/N ratio		**Deviation Sequence**		**Grey relational coefficient**		**Grey relational grade**	**Rank**
S.N.	***CF***	***SR***	***CF***	***SR***	***CF***	***SR***	***CF&SR***	***CF&SR***
1	-41.9	-44.9	1.000	0.000	0.422	1.267	0.844	18.000
2	-41.5	-44.5	0.133	0.133	1.000	1.000	1.000	27.000
3	-41.3	-44.3	0.200	0.200	0.905	0.905	0.905	22.000
4	-41.2	-44.2	0.233	0.233	0.864	0.864	0.864	19.000
5	-41.4	-44.5	0.167	0.133	0.950	1.000	0.975	25.000
6	-41.3	-44.3	0.200	0.200	0.905	0.905	0.905	22.000
7	-41.2	-44.2	0.233	0.233	0.864	0.864	0.864	19.000
8	-41.5	-44.5	0.133	0.133	1.000	1.000	1.000	26.000
9	-41.1	-44.1	0.267	0.267	0.826	0.826	0.826	17.000
10	-40.7	-43.8	0.400	0.367	0.704	0.731	0.717	13.000
11	-40.6	-43.6	0.433	0.433	0.679	0.679	0.679	11.000
12	-40.9	-43.9	0.333	0.333	0.760	0.760	0.760	14.000
13	-40.6	-43.6	0.433	0.433	0.679	0.679	0.679	11.000
14	-40.9	-43.9	0.333	0.333	0.760	0.760	0.760	14.000
15	-41.2	-44.2	0.233	0.233	0.864	0.864	0.864	19.000
16	-40.5	-43.5	0.467	0.467	0.655	0.655	0.655	10.000
17	-41.3	-44.3	0.200	0.200	0.905	0.905	0.905	22.000
18	-40.3	-43.3	0.533	0.533	0.613	0.613	0.613	9.000
19	-39.8	-42.8	0.700	0.700	0.528	0.528	0.528	6.000
20	-39.4	-42.4	0.833	0.833	0.475	0.475	0.475	3.000
21	-40	-43	0.633	0.633	0.559	0.559	0.559	7.000
22	-39.5	-42.5	0.800	0.800	0.487	0.487	0.487	5.000
23	-40	-43	0.633	0.633	0.559	0.559	0.559	7.000
24	-40.9	-43.9	0.333	0.333	0.760	0.760	0.760	14.000
25	-39.4	-42.4	0.833	0.833	0.475	0.475	0.475	3.000
26	-39.1	-42.1	0.933	0.933	0.442	0.442	0.442	2.000
27	-38.9	-41.9	1.000	1.000	0.422	0.422	0.422	1.000

Microstructure Analysis

Figures 7 (a) and 7 (b) depict SEM analysis of machined surfaces for the first and last ranks provided by the GRA, respectively. It is evident that the prevailing temperature conditions affect the machined surface and unevenly shape the surface profile. Due to the development of debris globules, craters of various sizes, and surface fissures, it was discovered from the microstructure analysis that the machining process severely affects the surface. The surface topography of the workpiece is enhanced during high-speed MQL machining, resulting in fewer flaws such as cracks, holes, pores and surface pits.

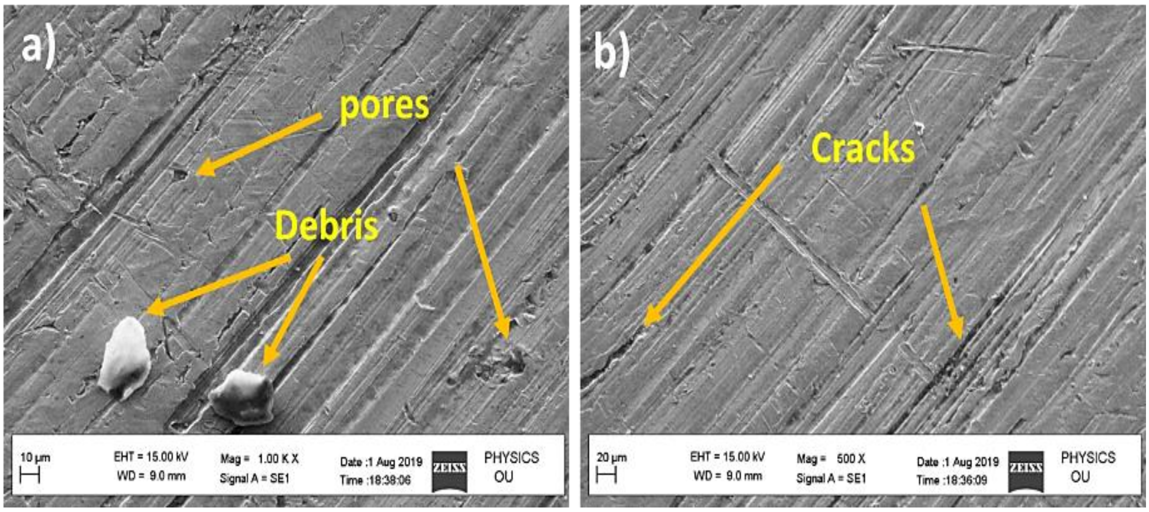

Figure 7. SEM image for (a) 2nd experimental run (b) 27th experimental run.

CONCLUSIONS

Experiments using nontoxic bio-degradable cutting fluid with various parameters and their levels by Taguchi orthogonal array (L27) lead to the following conclusion: Machining with the Minimal Quantity Lubrication (MQL) method consistently yielded the lowest CF compared to other lubrication systems, owing to reduced vibrations and friction.

1. Optimally, MQL machining at Vc 1000 rpm, f 90 mm/min, and a 0.3 mm minimized CF. Additionally, the cutting coolant (CC), a, Vc, and f contributed 77.77%, 6.54%, 4.606%, and 2.328% to CF reduction.
2. For SR, MQL machining similarly outperformed other methods, with MQL at Vc 1000 rpm, f 30 mm/min, and 0.45, producing the smoothest surfaces. The lubrication type played the most significant role, followed by Vc and f. Grey Relational Analysis (GRA) and Taguchi methods assisted in optimizing parameters, with the 27th combination emerging as the best for CF and SR.
3. SEM analysis further revealed the impact of temperature conditions on surface quality, highlighting MQL's superiority in enhancing surface topography and minimizing defects.
4. This study underscores the benefits of MQL machining and the significance of specific parameter combinations in achieving superior cutting force reduction and surface quality improvements.

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