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Optimizing Deep Hole Drilling: A Comprehensive Study of Parameters and Non-Edible Vegetable Oil as a Cutting Fluid

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Objectives: Investigate the influence of various factors (speed, feed rate, depth of cut, drill diameter, tip angle, and cutting fluid) on the deep hole drilling process in EN 24 steel. Explore the use of non-edible vegetable oils (Neem oil, Karanja oil, and SAE 20W40) as environmentally friendly alternatives to petroleum-based lubricants. Optimize drilling parameters to improve performance outcomes such as roundness error, surface roughness, and material removal rate.
Methods: Employed the Taguchi method using an L27 orthogonal array to design experiments. Conducted trials on a VMC machine equipped with a solid carbide cutting tool. Utilized advanced statistical analyses, including ANOVA and Grey Relational Analysis, to explore relationships between drilling parameters and performance outcomes.
Findings: Non-edible vegetable oils significantly enhanced drilling performance compared to conventional cutting fluids and dry conditions. Statistical analysis revealed strong correlations between selected parameters and optimized outcomes, validating the potential of vegetable oils in machining applications.
Novelty: Demonstrates the potential of Neem oil, Karanja oil, and SAE 20W40 as sustainable and efficient cutting fluids for EN24 steel machining. Provides comprehensive insights into the dynamics of deep hole drilling, contributing to advancements in eco-friendly machining practices.
Keywords: Taguchi Method, Cutting Fluids, Non-Edible Vegetable Oils, Deep Hole Drilling, EN 24 Steel.

1. Introduction

Drilling is a fundamental process in the field of metal machining that provides a cost-effective way to remove metal while upholding strict quality standards [1]. In industrial settings, the pursuit of operational efficiency and quality assurance frequently faces obstacles, requiring a careful balancing act between precision and productivity. Finding this balance becomes especially important when drilling because controllable parameters like cutting fluid, cutting speed, feed rate, and depth of cut are intricately linked to factors like surface roughness, material removal rate (MRR), tool wear, cutting force, and hole diameter error [2].

Four key parameters cutting fluid, cutting speed, feed rate, and depth of cut that are thought to be modifiable are the subject of this research project. These factors have a direct impact on critical performance metrics that define productivity and guarantee the intended level of product quality, like surface roughness, MRR, and roundness error. This study's particular context is the drilling of EN24 steel with a VMC machine, a procedure that presents both opportunities and obstacles for optimization [3][4].

In order to traverse this complex terrain, the study employs the Taguchi technique, a strong methodology that permits process optimization via a small number of tests without requiring a comprehensive process model. By using this method, the study hopes to improve performance characteristics and expedite experimental studies, which will save a great deal of money and time. Following the Taguchi methodology, sophisticated statistical techniques like ANOVA and Grey Relational Analysis are utilized to further explore the complex correlations between the drilling parameters and the final results. This project aims to identify the ideal drilling parameters by fusing theoretical frameworks with real world testing. This will ultimately improve drilling precision, efficiency, and economic viability in industrial applications.

2. TAGUCHI METHOD

A well-known technique for parameter design and experimental planning, the Taguchi method provides a methodical framework for process optimization. The signal, or intended output mean, is distinguished from the 'noise,' or unwanted output standard deviation, using this method. An essential component of this methodology is the Signal to Noise (S/N) ratio, which measures the mean to standard deviation ratio [5]. Three forms of S/N ratios are used: lower-the-better, higher-the-better, and nominal-the-better, depending on the sort of characteristic being studied [4][6].

There are several essential phases involved in applying the Taguchi method. Quality attributes and pertinent process parameters are first determined and assessed. The number of levels for these factors as well as any possible interactions between them are then ascertained [7]. After that, these parameters are projected onto an appropriate orthogonal array. This array configuration serves as the basis for experiments, and the S/N ratio is computed from the experimental data. The experimental results are analysed using both the S/N ratio and Analysis of Variance (ANOVA). On the basis of this analysis, the ideal process parameter levels are then chosen [8][9].

Orthogonal Arrays, which provide a balanced set of experiments and ensure efficiency by limiting the number of trials, are key to the Taguchi method. The Signal to Noise ratios, devised by Dr. Taguchi, act as logarithmic functions of desired outputs. These ratios are essential for data interpretation and optimal outcome prediction in addition to acting as objective functions for optimization [6]. By employing a methodical approach, the Taguchi technique offers a sturdy framework for effective process optimization and experimental design, empowering scholars and professionals to improve the effectiveness and caliber of diverse industrial operations [10].

2.1 Higher the Better

To obtain optimal drilling performance, the higher the better quality characteristics for material removal rate (MRR) must be taken. The S/N ratio for the higher the better-quality characteristics can be expressed as:

$$\text{S/N ratio} = -10\log\left(1/n \sum_{k=1}^{n} \left(1/y^2\right)\right)$$ ….......(1)

2.2 Lower the Better

To obtain the optimal drilling performance, the lower the better quality characteristics for surface roughness must be taken. The S/N ratio for the lower the better quality characteristics can be expressed as:

$$\text{S/N ratio} = -10\log \sum_{k=1}^{n} y^2/n$$ ....(2)

3. Experiment Details

On a VMC machine, a number of tests were conducted to examine the effects of various parameters in deep hole drilling. The objective of these studies was to investigate the effects of cutting fluid, cutting speed, feed rate, and depth of cut on EN 24 Steel's surface roughness, material removal rate (MRR), and roundness error. A VMC machine (MODEL NO VF4 HASS) was used for the machining operation, and carbide-coated High Speed Steel (HSS) twisted drills were used.

3.1 Selection of cutting parameters and their levels

The VMC machine was used to conduct the deep drilling tests. Figure 1 shows a snapshot of the experimental setup

Figure 1. Experimental Setup

The cutting fluid used was SAE 20W40. High Speed Steel (HSS) twisted drills coated with carbide were used for the deep drilling operation. A drill with a diameter of 10 mm was chosen. Round EN24 steel bars of 40 mm in diameter and 100 mm in length were utilized as the work piece material. With cutting fluid present, the initial cutting settings were as follows: 200 r.p.m. speed, 0.1 mm/rev feed rate, and 80 mm hole depth. By adjusting the speed between 200 and 600 r.p.m., the feed rate between 0.1 and 0.3 mm/rev, and the depth of cut between 80 and 100 mm using three distinct cutting fluids (SAE20W40, Neem Oil, and Karnja Oil), the practical range for the cutting parameters was established. Table 1 displays the range of each adjustable parameter that was chosen based on the trail experiments.

Table -1 Deep Hole Drilling Process Parameters and Their Levels

Factors	Units	Levels	Values		
Cutting Speed	rpm	3	200	400	600
Feed	mm/rev	3	0.1	0.2	0.3
Depth of cut	mm	3	80	90	100
Cutting Fluid		3	A	B	C

3.2 Determination of Optimal Cutting Parameters and Orthogonal array experiment

To simplify the cutting experiments and determine the ideal cutting parameters, we examine the use of an orthogonal array in this section. Both the Analysis of Variance (ANOVA) and the Signal to Noise (S/N) ratio are used to examine the results of these tests. The cutting parameters that produce the lowest surface roughness are identified using these analyses, and they are subsequently confirmed.

The total degrees of freedom must be determined in order to select an orthogonal array that is suitable for our research. This computation determines how many comparisons between process parameters are necessary to determine their relative efficacy. A three-level process parameter, for example, corresponds to two degrees of freedom. The interaction degrees of freedom between two factors are indicated by the product of these degrees of freedom. The degrees of freedom of the orthogonal array should, in general, match or exceed those of the process parameters in question. As shown in Table 2, we used an L27 orthogonal array in our investigation and carried out a total of twenty-seven tests.

Table -2 L27 Orthogonal Array

Experiment No.	Cutting Fluid	Cutting Speed	Feed	Depth of cut
	A	B	C	D
1	1	1	1	1
2	1	1	2	2
3	1	1	3	3
4	1	2	1	2
5	1	2	2	3
6	1	2	3	1
7	1	3	1	3
8	1	3	2	1
9	1	3	3	2
10	2	1	1	2
11	2	1	2	3
12	2	1	3	1
13	2	2	1	3
14	2	2	2	1
15	2	2	3	2
16	2	3	1	1
17	2	3	2	2
18	2	3	3	3
19	3	1	1	3
20	3	1	2	1
21	3	1	3	2
22	3	2	1	1
23	3	2	2	2
24	3	2	3	3
25	3	3	1	2
26	3	3	2	3
27	3	3	3	1

3.3 Selection of response variables

A. Surface Roughness Characteristics

The primary goal of surface roughness characteristics in all machining processes is to improve surface finish. SJ 301 measures the properties of surface roughness. Therefore, "smaller the better" is the characteristic for roundness error.

B. Material Removal Rate (MRR)

In any machining operation, material removal rate is an important factor to enhance the productivity. Hence the characteristics for surface roughness is “larger the better”.

C. Roundness Error

The circular cross section is one of the most crucial basic shapes for engineering components. Numerous applications include circular shapes, and determining out of roundness often just called roundness is a crucial evaluation. Therefore, it is essential to measure roundness accurately to guarantee that these components operate as intended. Therefore, "smaller the better" is the characteristic for roundness error.

4 RESULT AND DISCUSSION

Using a drill with an HSS carbide coating, a number of tests are carried out on EN24 steel. Following machining, the components undergo testing for roundness error, material removal rate, and surface roughness using the appropriate protocols. The better the roundness error, the larger the MRR, and the smaller the surface roughness, the better the S/N ratios are. All of the findings are displayed in Tables 3 and 4. ANOVA and Taguchi analysis are computed using the Mini tab software application.

Table -3, Experimental Results of Output Responses

Sr No.	Cutting Fluid	Cutting Speed	Feed	Depth of cut	surface roughness (Ra) (μm)	MRR (g/min)	Roundness Error (mm)
1	A	200	0.1	80	3.67	1.240	0.0254
2	A	200	0.2	90	3.23	1.380	0.0321
3	A	200	0.3	100	4.15	0.980	0.0342
4	A	400	0.1	90	3.54	1.190	0.0244
5	A	400	0.2	100	3.08	1.390	0.0333
6	A	400	0.3	80	3.91	1.320	0.0423
7	A	600	0.1	100	2.28	1.730	0.0371
8	A	600	0.2	80	3.31	1.390	0.0412
9	A	600	0.3	90	3.22	1.480	0.0433
10	B	200	0.1	90	2.34	1.680	0.0384
11	B	200	0.2	100	2.38	1.690	0.0541
12	B	200	0.3	80	4.31	1.190	0.0572

13	B	400	0.1	100	2.32	1.920	0.0347
14	B	400	0.2	80	3.22	1.410	0.0563
15	B	400	0.3	90	3.32	1.340	0.0568
16	B	600	0.1	80	2.33	1.570	0.0272
17	B	600	0.2	90	3.21	1.470	0.0523
18	B	600	0.3	100	4.11	1.070	0.0555
19	C	200	0.1	100	3.83	1.210	0.0481
20	C	200	0.2	80	3.33	1.240	0.0634
21	C	200	0.3	90	4.36	0.990	0.0744
22	C	400	0.1	80	2.21	1.910	0.0446
23	C	400	0.2	90	3.26	1.290	0.0542
24	C	400	0.3	100	4.24	1.000	0.0699
25	C	600	0.1	90	3.33	1.320	0.0523
26	C	600	0.2	100	3.31	1.330	0.0725
27	C	600	0.3	80	4	1.26	0.0722

Table 4, S/N Ratios of Process Responses

Run	surface roughness (Ra) (µm)	MRR (g/min)	Roundness Error (mm)
1	-11.293321	1.868434	31.903326
2	-10.184050	2.797582	29.869899
3	-12.360962	-0.175478	29.319478
4	-10.980065	1.510939	32.252203
5	-9.771014	2.860296	29.551115
6	-11.843535	2.411479	27.473193
7	-7.158697	4.760922	28.612522
8	-10.396560	2.860296	27.702056
9	-10.157117	3.405234	27.270242
10	-7.384317	4.506186	28.313376
11	-7.531539	4.557734	25.336055
12	-12.689545	1.510939	24.852079
13	-7.309760	5.666025	29.193411
14	-10.157117	2.984382	24.989832

Run	surface roughness (Ra) (µm)	MRR (g/min)	Roundness Error (mm)
15	-10.422762	2.542096	24.913033
16	-7.347118	3.917993	31.308622
17	-10.130101	3.346347	25.629966
18	-12.276836	0.587676	25.114140
19	-11.663975	1.655707	26.357098
20	-10.448885	1.868434	23.958215
21	-12.789730	-0.087296	22.568541
22	-6.887845	5.620667	27.013303
23	-10.264352	2.211794	25.320014
24	-12.547317	0.000000	23.110456
25	-10.448885	2.411479	25.629966
26	-10.396560	2.477033	22.793240
27	-12.041200	2.007411	22.829256

4.1 S/N Ratio and ANOVA Analysis

4.1.1 Surface Roughness

Signal to noise ratios for Surface Roughness (Smaller the better)

Table -5, S/N Ratios of Process Responses

Level	Cutting Fluid	Cutting Speed	Feed	Depth of cut
1	-10.594	-11.022	-10.737	-10.636
2	-9.943	-10.310	-10.646	-11.016
3	-11.083	-10.287	-10.236	-9.967
Delta	1.140	0.735	0.501	1.049
Rank	1	3	4	2

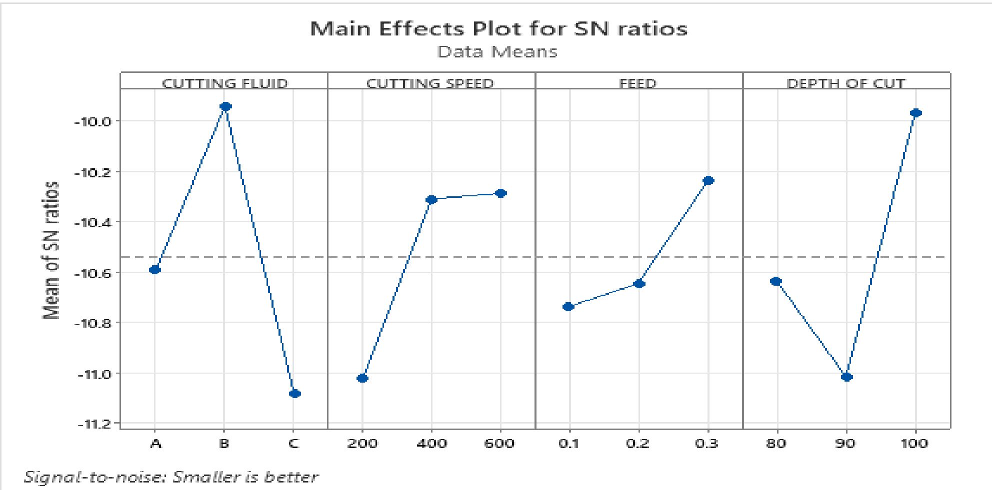

Figure 2. Main Effects Plot for SN Ratios (Ra)

The optimal parameters from the table 3 by Taguchi design for Ra are cutting fluid C, cutting speed=200 rpm, Feed rate = 0.1 mm/rev and depth of cut = 90 mm. The Figure 2 shows the Taguchi optimal parameters ($A_3B_1C_1D_2$) for Ra. The Results of the confirmation experiment for Ra and predicted value are shown in table 6.

Table-6, Results of the confirmation experiment for Surface Roughness

Confirmation experiment for Ra (µm)		
Level	Predicted value	Experimental results
A3B1C1D2	2.478	2.388

4.1.2 Material Removal Rate (MRR)

Signal to noise ratios for MRR (larger is better)

Table -7, S/N Ratios of Process Responses-MRR

Level	Cutting Fluid	Cutting Speed	Feed	Depth of cut
1	10.314	10.443	9.972	10.381
2	9.039	9.704	10.097	10.587
3	10.568	9.774	9.852	8.953
Delta	1.529	0.740	0.245	1.643
Rank	2	3	4	1

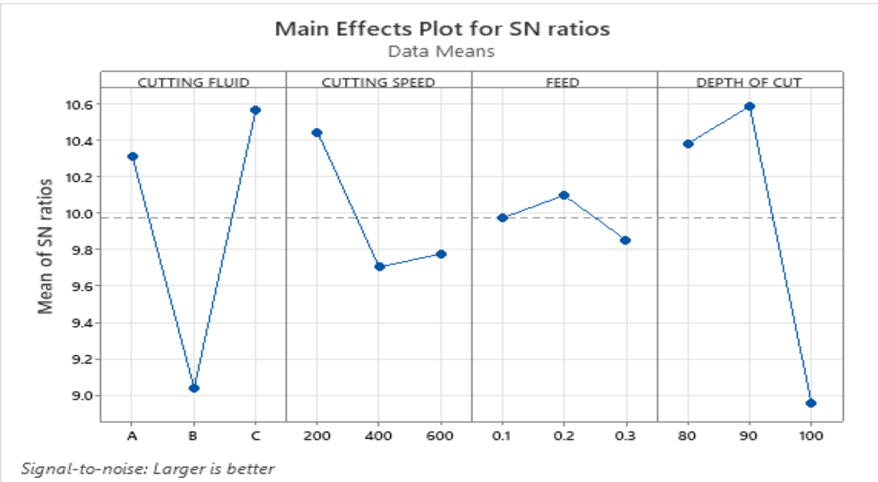

Figure 3, Main Effects Plot for SN Ratios -MRR

The optimal parameters from the table 3 by Taguchi design for MRR are cutting fluid C, cutting speed=200 rpm, Feed rate = 0.2 mm/min and depth of cut = 90 mm. The Fig 3 shows the Taguchi optimal parameters (A3B1C2D2) for MRR. The Results of the confirmation experiment for Ra and predicted value are shown in table 8.

Table-8, Results of the confirmation experiment for Material Removal Rate

Confirmation experiment for MRR (g/min)		
Level	Predicted value	Experimental results
A3B1C2D2	1.688	1.731

4.1.3 Roundness Error (RE)

Signal to noise ratios for RE (smaller is better)

Table -9, S/N Ratios of Process Responses-Roundness Error (RE)

Level	Cutting Fluid	Cutting Speed	Feed	Depth of cut
1	29.13	26.73	27.23	26.59
2	26.16	26.72	26.27	26.66
3	24.15	26.00	25.94	26.20

Delta	4.98	0.73	1.29	0.46
Rank	1	3	2	4

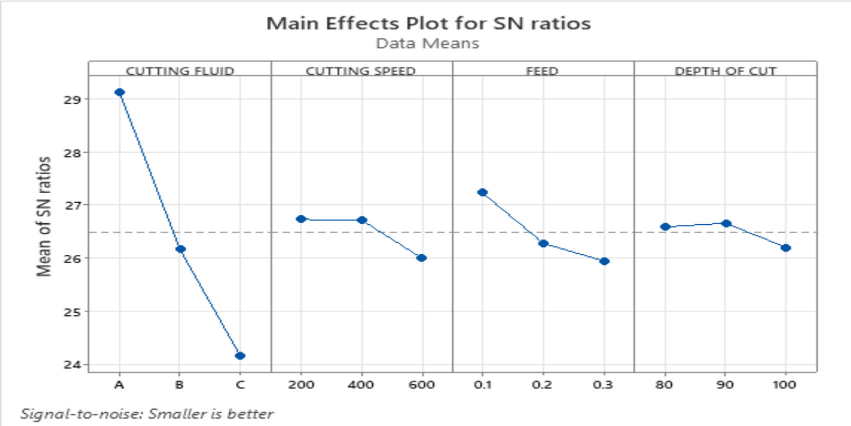

Figure 4. Main Effects Plot for SN Ratios Roundness Error

The optimal parameters from the table 3 by Taguchi design for MRR are cutting fluid C, cutting speed=600 rpm, Feed rate = 0.3 mm/min and depth of cut = 100 mm. The Figure 4 shows the Taguchi optimal parameters (A3B3C3D3) for RE. The Results of the confirmation experiment for RE and predicted value are shown in table 10.

Table-10, Results of the confirmation experiment for RE

Confirmation experiment for RE (mm)		
Level	Predicted value	Experimental results
A3B1C1D2	0.02072	0.0201

5 CONCLUSIONS

The Taguchi method's application to deep drilling operations' process parameter optimization has been the main focus of this study. Cutting fluid C, cutting speed = 200 rpm, feed rate = 0.1 mm/rev, and depth of cut = 90 mm were found to be the ideal cutting condition combination for achieving low surface roughness using the Taguchi method. It was observed that a 63.18 percent reduction in surface roughness was found at the Taguchi determined optimum cutting condition.

The Taguchi approach identified the ideal cutting parameters for achieving a high material removal rate, which were as follows: cutting fluid C, cutting speed = 200 rpm, feed rate = 0.2 mm/rev, and depth of cut = 90 mm. It was found that these parameters resulted in a 41.62 percent greater material removal rate.

Using the Taguchi method, the ideal cutting condition combination for achieving the low roundness error was determined to be cutting fluid C, cutting speed = 600 rpm, feed rate = 0.3 mm/rev, and depth of cut = 100 mm. It was found that the Taguchi determined optimum cutting condition resulted in a 63.73 percent reduction of surface roughness.

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