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Multiresponse optimization of hole number and surface roughness in drilling processes for 316L stainless steel material using Taguchi-grey relational analysis method

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Abstract

The drilling process involves creating a round hole using a drill bit. Using tools with improper parameter settings can result in component geometries with high inaccuracies and surface hole roughness and can also increase tool wear. This research aims to determine the optimal drill parameter settings to minimize two response variables, namely tool life and surface roughness on the workpiece. Experiments were conducted in the drilling process using 316L stainless steel material by setting a VB wear value of 0.2 mm. The experimental design uses an L9 orthogonal matrix with variations in tool diameter, spindle speed, feeding, and tool tip angle, each with three levels. The experiment was carried out with two replications. The Grey Relational Analysis (GRA) method was used to optimize the multi-response characteristics of experimental results with a longer tool life and a smaller surface roughness. The tool diameter was varied between 4 mm, 6 mm, and 8 mm. The tool diameter was varied at 4 mm, 6 mm, and 8 mm. Spindle speed was set at 597 rpm, 794 rpm, and 1194 rpm with feeding values of 30 mm/min, 38 mm/min, and 46 mm/min. The chisel tip angles used were 90°, 118°, and 135°. The result showed that the optimal setting was to implement a tool diameter of 4 mm, spindle speed of 796 rpm, a feeding rate of 38 mm/min, and a tool tip angle of 135°. After confirmation tests were carried out, this optimal combination produced 59 holes, or a tool life of 632.54 seconds, with a workpiece surface roughness of 0.680 µm. The tool tip angle was identified as the most influential factor, with a contribution of 59.80% to the observed multi-responses.

Keywords:

Drilling, gray relational analysis, number of holes, surface roughness, Taguchi method.

1 Introduction

The manufacturing process refers to a series of steps taken to change the shape of material with the aim of producing components that have the desired shape, size, and structure using certain materials. Machining is an important part of the manufacturing process and is closely related. In Indonesia, the manufacturing industry supported by machining processes has become one of the main pillars of growth in the non-oil and gas sectors. Currently, several manufacturing industry sectors that use machining processes in their operations have experienced significant growth.

The Ministry of Industry noted several sectors that had a performance percentage above the national Gross Domestic Product (GDP), including the basic metals industry at 9.94%. Apart from Indonesia, various manufacturing sectors are also being developed in other ASEAN countries, such as the Philippines and Vietnam. This will certainly encourage national economic growth and increase competitiveness domestically, regionally, and globally. This manufacturing industry is increasingly being developed by the government through downstream methods. This must be supported by increased investment and export performance to maintain the manufacturing industry and make it the largest contributor to taxes and customs duties. The development of the manufacturing industry in Indonesia must also be supported by cooperation from various parties, such as the government, entrepreneurs, and the general public. It should be noted that the MVA or Manufacturing Value Added value for the Indonesian manufacturing industry is in the highest position among ASEAN countries, with an achievement of 4.5%. Meanwhile, globally, Indonesian manufacturing is ranked 9th out of all countries in the world.

One of the advantages of 316L stainless steel is its resistance to corrosion, strong mechanical properties, toughness, elasticity, and easy-to-clean surface. An example of the application of 316L stainless steel material in the medical world is shown in Fig. 1. Because of its strong mechanical properties, the machining process also influences the reliability of the chisel or cutting tool.

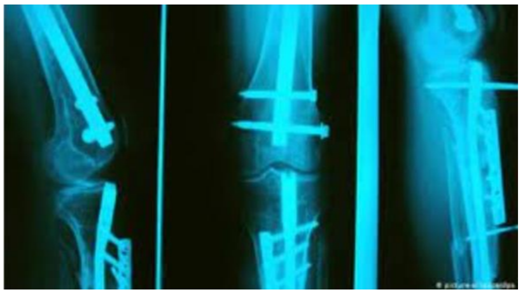


Fig. 1. Application of SS 316L as a bone connector implant.

Numerous studies have been conducted on the machining of SS 316L. Sultan (2015) investigated the drilling process on SS 316L material using uncoated carbide cutting tools with a diameter of 4 ± 0.01 mm, a point angle of 135º, and a helix angle of 30º at spindle speeds of 18 and 30 m/min and feed rates of 0.03, 0.045, and 0.06 mm/rev. The errors in hole diameter and surface roughness were mainly influenced by cutting speed and feed rate. Meanwhile, the feed rate and cutting speed did not have a significant impact on circularity. In other words, as the cutting speed increased, surface roughness decreased. Conversely, as the feed rate increased, the surface roughness value also increased. At the same time, tool wear affected surface roughness. For cylindrical errors, lower cutting speeds and lower feed rates provided better results. Regarding diameter size deviations, the feed rate had more influence compared to cutting speed. During the drilling of stainless steel, the drill experienced similar failure modes at all cutting speeds and feed rates used, including uneven flank wear, chipping, and catastrophic failure.

Bhole *et al.* (2016) conducted a study on drilling processes on SS 316L material. They stated that the Taguchi approach was sequentially applied to obtain optimal drilling operation outcomes on Alloy 316L, aiming for minimum surface roughness and material removal rate, with feed rate being the most influential factor, followed by spindle speed [1].

In his paper, Sharidan (2014) presented the influence of drilling parameters on tool wear, tool life, surface roughness, dimensional accuracy, and circularity when drilling SS 316L material using HSS tools. The experiments were conducted at various cutting speeds of 10, 16, and 22 m/min with constant feed rates of 0.05 and 0.075 mm/rev, under both dry and coolant conditions. The results showed that the number of successfully drilled holes was significantly influenced by the cutting speed, where higher cutting speeds resulted in fewer holes. Surface roughness measurements showed better results at lower cutting speeds and feed rates. The results also indicated that dimensional accuracy was better at lower feed rates compared to higher feed rates. In terms of circularity, it was found that new tools provided better circularity compared to worn tools [2].

Cicek *et al.* (2012) conducted a study on the machining behavior of SS 316 material using HSS twist drills that had undergone cryogenic treatment and those that had not. The machining behavior of SS 316 was evaluated based on thrust force, tool life, surface roughness, and the quality of drilled holes. The experimental results showed an increase in tool life from 14% to 218% for tools that had been treated. Thrust force, surface roughness, and hole quality were also better with treated tools compared to untreated drills. This improvement was largely attributed to the formation of fine and homogeneous carbide particles as well as the transformation of retained austenite into martensite. Microhardness and microstructure observations also verified these formations [3].

Rao *et al.* (2021) conducted an analysis using a combination of Taguchi and Grey Relational Analysis (GRA) methodologies. This approach was utilized for multi-response experimental data collected for drill flank wear and surface roughness. GRA transformed the multi-response characteristics into a single performance characteristic by generating GRG. The analysis revealed that a spindle speed of 1200 rpm, a drill feed of 0.2 mm/rev, and a drill diameter of 6 mm would minimize drill flank wear and surface roughness. Further GRG analysis with the Analysis of Variance (ANOVA) technique applied to the average GRG values concluded that drill diameter had the highest significance (46.97%), followed by drill feed rate (20.37%) and spindle speed (16.10%) on GRG. Confirmation tests were conducted to verify the validity of GRG optimization, showing a 6.9% increase in experimental GRG values [4].

Ahmed *et al.* (2018) stated that based on Analysis of Variance (ANOVA), the most effective parameters for tool life have been determined. Specifically, the tool material is the primary factor that has the highest impact on tool life. This factor has an influence approximately 1.7 and 2.62 times higher for AISI 304 and AISI 2205, respectively, which is more significant than the second-ranked factor (cutting speed). Feed rate seems to have no significant influence on tool life [5].

Ammouri *et al.* (2011) state in their scientific paper that as the drilling process progresses, wear occurs on the cutting tool, causing the drill bit to transition from a sharp condition to partially worn and ultimately to a dull or completely worn condition. Severe failure occurs when drilling is performed using a dull tool. Wear on the drill bit occurs in all areas that come into contact with the metal during drilling. However, among the various types of wear studied, flank wear (VB) is the most common in the metal cutting literature. Although many methods are used to measure flank wear, including taking the average wear distance at specific locations on the drill edge, this research employs maximum flank wear, VBmax, at the point where the edge meets the flank and the cutting speed is highest [6].

From the explanations above, it can be concluded that numerous studies have observed the relationship between machining responses and machining factors or parameters, both single responses and multi-responses. Multi-response optimization research is highly beneficial for determining the optimal combination of each machining parameter, allowing for the simultaneous optimization of multiple responses in a single experiment. This plays a crucial role in the manufacturing industry by enhancing production efficiency. Therefore, the aim of the study conducted by the author is to determine the optimal conditions for the drilling and machining process on stainless steel 316L alloy material by observing two responses: the number of holes and the surface roughness of the workpiece. The number of holes will be calculated based on the progress of the tool's condition during the machining process until it is deemed worn out. The parameters to be observed include drill diameter, spindle speed, feeding rate, and tool tip angle. The method to be employed is a combination of the Taguchi method and GRA. In other words, this research will seek the optimum conditions of four machining factors to achieve maximum hole count and minimal workpiece surface roughness.

SS 316L is a type of steel known for its corrosion resistance, strong mechanical properties, toughness, elasticity, and easily cleanable surface. Therefore, its tough mechanical properties during machining processes significantly influence the reliability of the cutting tool.

In research conducted by Sulthan, (2015), it was said that the SS 316L drilling process used an uncoated carbide tool with a diameter of 4 ± 0.01 mm with a point angle of 135º and a helix angle of 30º at spindle speeds of 18 and 30 mmin-1 and a feed rate of 0.03, 0.045, and 0.06 mm/rev. Hole diameter error and surface roughness are mostly influenced by cutting speed and feed rate. Meanwhile, feed rate and cutting speed do not have a significant influence on the circularity error value. In other words, as the cutting speed increases, the surface roughness decreases. Conversely, when the feed rate increases, the surface roughness value increases as well. At the same time, tool wear affects the surface roughness. For hole cylindricity, lower cutting speeds and lower feed rates will provide better results. In terms of diameter error, feed rate is more influential than cutting speed. During drilling of austenitic stainless steel, the drill experiences similar failure modes at all cutting speeds and feed rates used, namely non-uniform flank wear, chipping, and catastrophic failure [8].

Based on Analysis of Variance (ANOVA), the most effective parameters for tool life have been determined. In particular, tool material is the main factor that has the highest impact on tool life. This factor has approximately 1.7 and 2.62 times the influence for AISI 304 and AISI 2205, respectively, which is more important than the second ranking factor (cutting speed). The feed rate does not appear to have a significant effect on tool life.

As the drilling process progresses, wear occurs on the cutting tool, which causes the sharpness of the drill bit to change from 'sharp' to worn and finally to 'dull' or 'wear out'. Very serious failures occur when drilling is carried out using blunt tools. Of the many types of wear studied, flank wear VB is the most common in the metal cutting literature. Although many methods are used to measure flank wear, including taking the average wear distance at a particular location on the drill lip, this study used the maximum VB, VBmax, at the point where the lip meets the edge and the cutting speed is highest.

Many factors influence the machining process. One of them is the wear of the chisel or cutting tool and the increase in temperature experienced by the tool. These factors have a significant impact on tool life and performance.

Many factors influence the machining process, including the wear of the chisel or cutting tool and the increase in temperature experienced by the tool. These factors have a significant impact on tool life and performance. From the literature above, many research have observed the influence of machining parameters on wear response, tool life, and surface quality response. Therefore, research on optimizing machining parameters for multiple responses is highly useful for determining the optimal combination of each machining parameter, allowing for the simultaneous optimization of multiple responses in a single experiment. This plays a crucial role in the manufacturing industry by enhancing production efficiency.

2 Method

2.1 The Cutting Tool

The cutting tool used was a High-Speed Steel (HSS) twist drill bit with the brand NACHI, planned to come in three diameters: 4, 6, and 8 mm (Table 1). HSS twist drills are alloys composed of 0.75%-1.5% Carbon (C), 4%-4.5% Chromium (Cr), 10%-20% Tungsten (W) and Molybdenum (Mo), 5% or more Vanadium (V), and Cobalt (Co) exceeding 12% (Fig. 2).

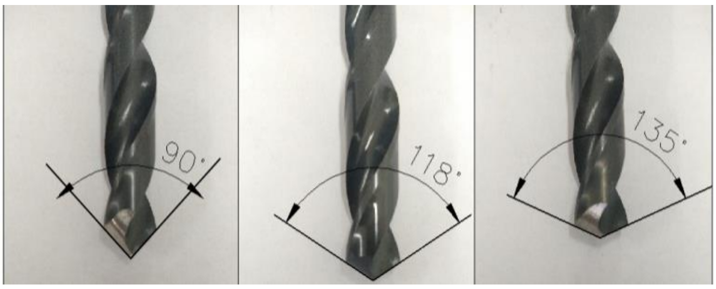


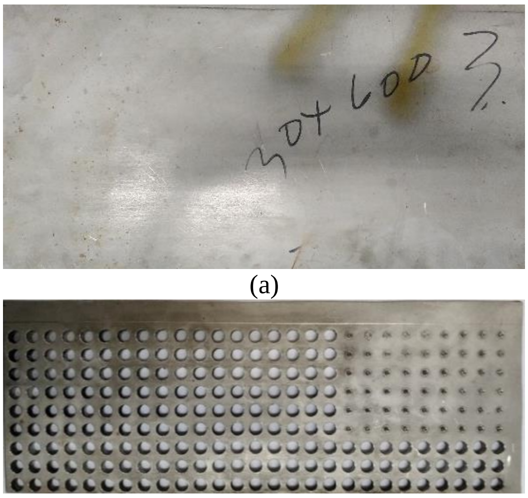
Fig. 2. Twist drill point angle.

Table 1. Twist drill specification

Description	Specification
Brand name	Nachi product
Diameter	4 mm, 6 mm, 8 mm
Code	BO821, BO844, BO816
Material	HSS standard LIST 500
Type	Standard Parallel Shank
Number of flutes	2
Twist angle	30°
Point angle	90^o, 118°, 135^o
Flute length	43 mm, 70 mm, 80 mm
Total length	73 mm, 102 mm, 117 mm
Diameter tolerance	H8
Point angle	90^o, 118^o, 135^o

2.2 The Work Piece

The workpiece used in this research was 316L stainless steel alloy in the form of a plate with a thickness of 6 mm, a length of 600 mm, and a width of 300 mm. The holes distance in this research was 1.5D (Fig. 3).



(a)

(b)

Fig. 3. Stainless steel 316L (a) before drilling process (b) after drilling process.

2.3 Design of Experiment and Analysis

The research to be conducted involves the drilling and machining process with four factors, each with three levels and two responses. The four factors are drill bit diameter, spindle rotation speed, feed rate, and tool tip angle. The response variables to be investigated are the number of holes and the surface roughness of the workpiece. The parameter values set for the experimental factors are as shown in Table 2.

Table 2. Machining parameter

Code	Machining parameter	Unit	Level 1	2	3
A	Tool diameter	mm	4	6	8
B	Spindle speed	rpm	1194	796	597
C	Feeding	mm/mnt	46	38	30
D	Point angle	o	90	118	135

3 Results and Discussion

3.1 Result

The number of holes was determined by conducting two repetitions, ensuring the reliability of the data. During drilling, the drill bit wear was monitored, with each run order maintaining a wear threshold of 0.2 mm. This threshold ensured consistency across the repetitions, allowing for accurate measurement of the number of holes achieved. Surface roughness response was measured with three repetitions at the beginning of the hole, the middle, and the end of the number of holes for each run order, thus producing an average surface roughness (Table 3).

Table 3. Research data

Run order	Dia	Spindle speed	Feeding	Angle	Number of holes	SR
1	4	1194	46	90	21	0.785
2	4	796	38	118	39	0.680
3	4	597	30	135	27	0.815
4	6	1194	38	135	27	1.057
5	6	796	30	90	18	0.773
6	6	597	46	118	24	0.708
7	8	1194	30	118	6	1.018
8	8	796	46	135	6	1.035
9	8	597	38	90	6	0.843

The next step was to calculate the S/N ratio and process the data using the Taguchi method to obtain the optimal combination of factors for each response (Table 4). The characteristic of the JL response is "larger the better". Eq. 1 used:

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

And the smaller the SR response characteristic the better. Eq. 2 used:

$$S/N\ R\_STB = -10\log[Xi(j)^2] \quad (2)$$

Table 4. S/N ratio

Run order	SN number of holes (larger the better)	SN SR (smaller the better)
1	26.444	2.103
2	31.821	3.350
3	28.627	1.777
4	28.627	-0.479
5	25.105	2.233
6	27.604	2.995
7	15.563	-0.152
8	15.563	-0.302
9	15.563	1.480

The Taguchi method is utilized to find the best conditions for a single response. However, to achieve optimal conditions for multiple responses, the Taguchi method can be combined with Grey Relational Analysis (GRA). By using this combination, it is expected that determining the optimum conditions for multiple parameters can be done more efficiently. Through GRA, research with a small number of samples and limited information can be analyzed to obtain optimal conditions. The result produced by GRA is a single value of the optimization of multiple responses, often referred to as the Grey Relational Grade (GRG).

Finding an optimum value for each response using Minitab 16 software (Fig. 4 and Fig. 5).

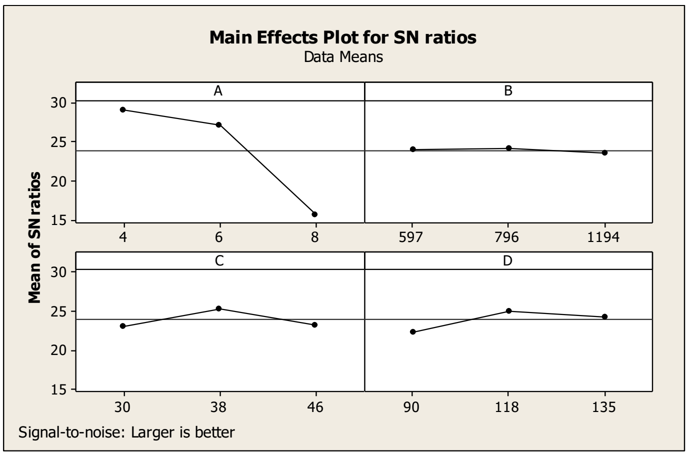


Fig. 4. Main effect plot for S/N ratio number of holes.

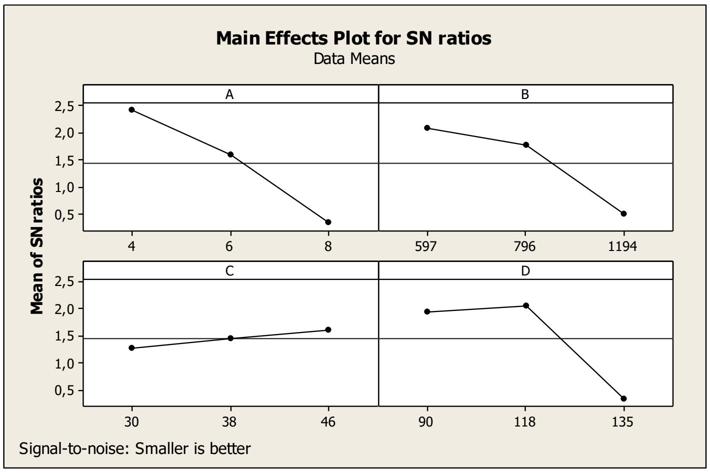


Fig. 5. Main effect plot for S/N ratio surface roughness.

From the graph it can be seen that the optimal factors for each response are as shown in Table 5.

Table 5. The optimum factor for both responses

Respon	Optimal factor			
Number of holes	A1	B2	C2	D2
Surface roughness	A1	B1	C3	D2

Given that for both experimental responses, different optimal factors were obtained. The optimal factor combination for the Number of Holes (JL) response is a 4 mm drill bit diameter, a spindle speed of 796 rpm, a feed rate of 38 mm/minute, and a tool tip angle of 118°. Meanwhile, the optimal factor combination for the Surface Roughness (SR) response is a 4 mm drill bit diameter, spindle speed of 1194 rpm, feed rate of 30 mm/minute, and a tool tip angle of 118°.

Next, a two-way ANOVA will be conducted to determine the significance of each factor in the response. Using Minitab software, the ANOVA results for each response can be obtained. Since the Taguchi method does not involve replication of responses, and if there is replication, the values will be averaged, it is not possible to conduct an ANOVA with nine run orders, four factors, and three levels. Therefore, replications of each response will be added and considered as run orders, resulting in 18 run orders. The calculation results will be obtained using Minitab software and the number of holes (Table 6).

```
General Linear Model: Number of Hole versus tool
diameter; Spindle speed; Feeding; Point Angle
Factor              Type        Levels    Values
Tool diameter       fixed          3      4; 6; 8
Spindle speed       fixed          3      597; 796; 1194
Feeding             fixed          3      30; 38; 46
Point Angle         fixed          3      90; 118; 135

Analysis of Variance for tool life, using Adjusted SS
for Tests
Source        DF   Seq SS   Adj SS   Adj MS      F       P
Tool dia       2  1708.00  1708.00  854.00   768.60  0.000
Spindle        2    28.00    28.00   14.00    12.60  0.002
Feeding        2   196.00   196.00   98.00    88.20  0.000
Point Angle    2   196.00   196.00   98.00    88.20  0.000
Error          9    10.00    10.00    1.11
Total         17  2138.00
```

Table 6. Percent contribution of each factor to the number of holes response

Factor	Adj SS	Contribution
Tool diameter	1708.00	79.88 %
Spindle speed	28.00	1.31 %
Feeding	196.00	9.16 %
Point angle	196.00	9.16 %
Error	10.00	0.47 %
Total	2138.00	100 %

For the response to the number of holes, with F table = F (0.05; 2; 17) = 3.59, it was found that the tool diameter factor had a significant effect, F-count = 768.6 > 3.59 with a contribution percentage of 79.88%. The spindle speed factor has a significant effect because F-count = 12.60 > 3.59 with a contribution percentage of 1.31%. The feeding factor has a significant effect because F-count is 88.20 > 3.59 with a contribution percentage of 9.16%. The tool tip angle factor also has quite a significant effect, where F-count = 88.20 > 3.59 with a contribution percentage of 9.16%. Of all the factors, the one that has the largest contribution, namely above 50%, is the tool diameter factor. Because the optimal factor with the greatest contribution is the tool diameter factor, we will see further whether this factor is also significant for other responses, namely surface roughness.

And below are the results of ANOVA calculations using Minitab 16 software for surface roughness:

```
General Linear Model: Surface Roughness versus Tool
Diameter pahat; Spindle speed; Feeding; Point Angle
Factor             Type      Levels   Values
Tool diameter      fixed        3     4; 6; 8
Spindle speed      fixed        3     597; 796; 1194
Feeding            fixed        3     30; 38; 46
Point Angle        fixed        3     90; 118; 135

Analysis of Variance for Surface Roughness, using
Adjusted SS for Tests
Source       DF   Seq SS    Adj SS    Adj MS     F      P
Tool dia      2  0.074470 0.074470 0.037230 1.08  0.379
Spindle       2  0.123620 0.123620 0.061810 1.80  0.220
Feeding       2  0.051320 0.051320 0.025660 0.75  0.501
Point Angle   2  0.215310 0.215310 0.107650 3.13  0.093
Error         9  0.309150 0.309150 0.034350
Total        17  0.773870
```

The results of calculating the percent contribution of factors to the surface roughness response (based on the Adj-SS value) are as shown in Table 7.

Table 7. Percentage contribution of each factor to surface roughness

Factor	Adj SS	Contribusion
Tool diameter	0.07447	9.623 %
Spindle speed	0.12362	15.974 %
Feeding	0.05132	6.632 %
Point angle	0.21531	27.823 %
Error	0.30915	39.949 %
Total	0.77387	100 %

For surface roughness, almost all factors do not have a significant influence, where F-count < 3.59. In order of percentage contribution from highest to lowest, there is the tool tip angle factor with a contribution percentage of 27.823%, then the spindle speed factor of 15.974%, followed by the tool diameter factor of 9.623%, and finally the feeding factor of 6.632%.

Complete results from SNR optimization and ANOVA as shown in Table 8.

Table 8. S/N Ratio and ANOVA optimization results

Responses	Taguchi method	
	Optimum combination parameter	Significancy
Number of holes	A1 B2 C2 D2	Tool diameter (79.88 %) Feeding (9.16 %) Point angle (9.16 %) Spindel speed (1.31 %)
Surface roughness	A1 B1 C3 D2	Point angle (27.823 %) Spindel speed (15.974 %) Tool diameter (9.623 %) Feeding (6.632 %)

The results of SNR optimization and ANOVA analysis show the optimal factor combination and significant factors for the two observed responses: the number of holes and surface roughness. Here is the analysis for each response:

1. Number of holes

The optimal factor combination is A1, B2, C2, D2, and the contributing factors are tool diameter (79.88%), feeding (9.16%), tool tip angle (9.16%). Based on the optimization results, the optimal combination of factors to achieve the desired number of holes is to use a tool, with diameter A1 (4 mm), feeding B2 (38 mm/minute), spindle speed C2 (796 rpm), and tool tip angle D2 (118^{o}). The most significant factor influencing the number of holes is tool diameter, with a contribution of 79.88%, followed by feeding, with a contribution of 9.16%, and tool tip angle, with a contribution of 9.16%.

2. Surface roughness

The optimal factor combination is A1 B1 C3 D2, and significant factors are tool tip angle (27.823%), spindle speed (15.974%), tool diameter (9.623%), and feeding (6.632%).

To achieve the desired surface roughness, the optimal factor combination used is a drill bit with diameter A1 (4 mm), feeding rate B3 (30 mm/minute), spindle speed C2 (796 rpm), and tool tip angle D1 (90°). The most significant factor influencing surface roughness is the tool tip angle, with a contribution of 27.823%, followed by spindle speed, with a contribution of 15.974%.

Through the optimized application of the Taguchi method, the best factor combinations for both responses were successfully revealed. Additionally, through ANOVA analysis, significant factors were identified, providing valuable insights into the influence of each factor on the observed responses.

From the obtained data, the drill bit diameter factor emerged as a significant factor for the number of holes response and contributed significantly to the surface roughness response as well. This will be further examined using the Grey Relational Analysis (GRA) method to determine whether the drill bit diameter factor will indeed be significant for multi-response.

3.2 Taguchi–GRA Multiresponse Analysis

The Taguchi-GRA method allows for the assessment of combined performance from various responses by integrating them into a single performance criterion, the Grey Relation Grade (GRG). Thus, we can search for parameter combinations that yield the best results for all quality characteristics (Table 9).

The combination of Taguchi and GRA methods provides a robust and systematic approach to optimizing manufacturing process parameters with high efficiency and yields better results in various fields of the manufacturing industry (Table 10).

Table 9. SNR normalization

Run order	S/N R normalization	
	Number of holes	Surface roughness
1	0.669	0.326
2	1.000	0.000
3	0.804	0.411
4	0.804	1.000
5	0.587	0.292
6	0.741	0.093
7	0.000	0.915
8	0.000	0.954
9	0.000	0.488
max	1.000	1.000
min	0.000	0.000

From the Table 11, it can be observed that the largest GRG value is found in the second run order, indicating that the initial parameters lie in the combination of factors A1, B2, C2, and D2. However, these initial parameters do not yet represent the true optimization values. Next, we can search for the average GRG values to determine the optimal conditions for each factor.

Tabel 10. Delta value and GRC

Run order	Delta		GRC	
	Number of holes	SR	Number of holes	SR
1	0.331	0.674	0.602	0.426
2	0.000	1.000	1.000	0.333
3	0.196	0.589	0.718	0.459
4	0.196	0.000	0.718	0.500
5	0.413	0.708	0.548	0.414
6	0.259	0.907	0.658	0.355
7	1.000	0.085	0.333	0.854
8	1.000	0.046	0.333	0.915
9	1.000	0.512	0.333	0.494

Table 11. Grey Relational Grade (GRG)

Run order	GRG	Rank
1	0.514	6
2	0.667	1
3	0.588	5
4	0.609	4
5	0.481	8
6	0.507	7
7	0.594	2
8	0.624	3
9	0.414	9

From the Table 12, it can be seen that the optimal value of all responses can be achieved if the experimental factors are set at A1, B2, C2, and D3. This combination of factors is not present in the nine experimental run orders that have been carried out.

Table 12. GRG optimation

Level	Factor			
	A	B	C	D
Level 1	0.590	0.572	0.554	0.469
Level 2	0.532	0.591	0.563	0.589
Level 3	0.544	0.503	0.548	0.607
Max	0.590	0.591	0.563	0.607
Min	0.532	0.503	0.548	0.469
diff	0.057	0.088	0.015	0.138
Rank	3	2	4	1

To find out the predicted value of GRG in the combination of factors A1, B2, C2, and D3, the equation is used:

γ_m = GRG average = 0.555
$\overline{\gamma_i}$ = GRG on each optimal level
for A1, $\overline{\gamma_i} = 0.590$
for B1, $\overline{\gamma_i} = 0.591$
for C1, $\overline{\gamma_i} = 0.563$
for D3, $\overline{\gamma_i} = 0.607$
GRG prediction =
$(0.555 + ((0.590 - 0.555) + (0.591 - 0.555) + (0.563 - 0.555) + (0.607 - 0.555) = 0.555 + (0.035 + 0.0036 + 0.008 + 0.0052) = 0.555 + 0.0139 = 0.518$

So the predicted GRG for the optimal combination of factors A1, B2, C2, and D3 is 0.518. The predicted value will then be tested for validity with a confirmation test.

4 Conclusion

1. Using the Taguchi method, the research results reveal that all machining factors observed have a significant impact on the response to the number of holes formed, where the factor that has the most dominant contribution is tool diameter with a participation rate of 79.88%. Meanwhile, the tool tip angle factor also has a significant influence on the surface roughness of the workpiece, with a contribution level reaching 27.82%.

2. Through the application of the Gray Relational Analysis (GRA) method, it was found that the optimal combination of the most effective experimental factors was a tool diameter of 4 mm, spindle speed of 796 rpm, feeding of 38 mm/minute, and a tool tip angle of 135°. The tool tip angle factor shows the most significant influence, with a contribution reaching 59.80% in the experimental results.

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