Optimization of Machining Parameters for Drilling on EN-24 Material Using the Taguchi Technique

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Abstract High-quality CNC machining depends on proper operator skills as well as optimum factor selection for the machine. The current study aims to establish the relationship between response parameters such as tool wear rate (TWR) and input variables such as spindle speed, feed rate, and depth of cut. Analysis was done using the DOE technique named 'Taguchi' and optimized parameters were determined by using ANOVA. The validity of the trials can be confirmed by displaying the predicted and experimental values of the optimal solution's TWR response range. This study came to the conclusion that when drilling EN-24 steel, the depth of the cut is the most important component, whereas spindle speed is the factor that contributes the least to effective machining.

Keywords CNC drilling · EN-24 · Optimization of TWR · DOE · Taguchi · ANOVA

1 Introduction

In production engineering where material removal is one important industrial process, CNC drilling is an important industrial requirement, like other machining work CNC drilling has also issues like product quality, surface finish production time, and many more. These issues are taken by researchers to improve CNC drilling machining for different types of material objects. In CNC manufacturing especially in CNC drilling conditions to reduce the involvement of human interface to reduce errors and quality issues, researchers try to work on find out suitable conditions for manufacturing of CNC drilling by selection of machining parameters for selective object materials

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H. Kumar et al. (eds.), *Recent Advances in Intelligent Manufacturing*,
Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-99-1308-4_33

with proper cutting tool selection. In this study, the Taguchi method is utilized to achieve optimal results for TWR.

Ozler et al. [1] examined the influence of response parameters such as washer geometry, length of bush and petal geometry on drilling of square shaped AISI 10 steel tube. According to the findings, the length of the bushing is distorted when the feed rate is increased, but it is improved when the bushing is longer. Ku et al. [2] utilized the ANOVA method to investigate the influence of spindle speed, friction angle, friction area, and feed rate during drilling of the 2 mm thick plate of SS 304 steel. According to the findings, the element that had the greatest impact on the surface roughness was the spindle speed, followed by the feed rate. On the other hand, the friction area had a considerable bearing on the length of the bushing. Tyagi et al. [3] evaluated the effects of speed, feed and depth of cut on SR and MRR during drilling of mild steel through HSS drill. The study reported that SR and MRR were most significantly influenced by speed and feed respectively. Sharma et al. [4] proposed Taguchi technique to investigate the performance of CNC drilling for ovality of drilling hole and SR on AISI 304 steel. Results revealed that feed rate and depth played a significant role for SR and ovality of hole. SR is most significantly influenced by feed rate followed by depth of cut whereas ovality is affected by depth of cut followed by feed rate. Rajaparthiban et al. [5] suggested the Taguchi approach for finding the optimal solution for various machining parameters. Results revealed the good agreement between predicted results and experimental results. Kalyankumar et al. [6] examined the influence of cutting speed, feed rate and cutting depth on TWR by using grey relational analysis (GRA). The results revealed that GRA technique can effectively improve the response speed of the turning process.

Chow et al. [7] performed an investigation on the sintered carbide drill that was used for drilling the sheet of the AISI 304 steel. During the course of the analysis, a Taguchi, L-18 orthogonal array was utilized. The drilling speed, the friction contact area ratio, the friction angle, and the feed rate were the input parameters, while surface roughness was the output parameter. For demonstration of surface roughness microstructure investigation was performed. Outcomes revealed that high hardness along with fine grain structure were found in the area near the drilled hole.

Hýþman Çelik [8] investigated the influence of the process parameter such as feed (0.05–0.15 mm/rev), cutting speed (12.5–25 m/min) and twist drill (900–1400 point angles) effects on drilling of Ti-6Al-4 V alloy. The main response during the investigation were chip formation, hole quality, surface roughness and burr height. The results showed that with higher speed a decrement was observed in surface roughness, and with higher point angle and feed rate a decrement was observed in burr height. Increase in burr height was observed at high speed. At higher feed and point angles increase in hole diameter was observed and was closed to nominal size at high speed. Experiments on drilling the AISI 304 stainless steel were carried out by El-Bahloul et al. [9], who employed the Taguchi method and the fuzzy logic approach in order to optimize the drilling process. It was suggested that these approaches were simple and capable for multi-objective optimization. To minimize the delamination factor in drilling operation of CFRPs. Gaitonde et al. [10] provided evidence that demonstrated the approach of Taguchi technique optimization. Experiments were conducted utilizing an L-27 orthogonal array, and the process parameters speed, feed, and point angle were taken into consideration. For finding the optimum process parameters for delamination, factor ANOVA was used. Finally it was revealed that for minimum delamination factor, the point angle, then feed and speed were the notable factors. Somasundaram et al. [11] investigated the roundness errors of the drilled holes under varying feed rate, spindle speed, work-piece thickness and percentage weight of reinforcement particles on aluminum matrix composite sheets using high speed steel drill. They proposed RSM to prove the effect of process parameters to minimize the roundness error. The outcomes showed that with the increase in the percentage of reinforcement in aluminum metal matrix composites, roundness error decreased whereas other input process parameters increased the roundness error. Han et al. [12] carried out an experiment on Ti6Al4V to improve the quality of hole exit like burr formation and surface finish. The alpha- beta titanium alloy Ti6Al4V was used as the work-piece. Drilling operations were performed on BJXK5070 five axis high speed machining center. Input parameters were taken as the cutting speed (30 rpm, 60 rpm, 90 rpm and 110 rpm), feed (0.07 mm/rev, 0.08 mm/rev, 0.09 mm/rev and 0.10 mm/rev) for hole diameter of 8 mm. According to the findings, the burr's width and height increased as the feed rate was increased, even though the spindle speed remained the same. If the feed rate remains the same, the burr height will grow proportionally with the spindle speed. Heisel et al. [13] carried out a study on the angle of the drill point while drilling on the carbon fiber reinforced plastic. Experiments were performed using cutting speed (21–513 m/min) and feed (0.05–0.40 mm/rev). Cemented carbide drill having varying point angles (155°, 175° and 185°) was used in experiments. The results revealed that with increase in point angle and feed improved the quality of drill hole at entrance but decreased the quality at exit. An investigation was done on the drilling operation by Miller et al. [14] on the AISI 1020 steel sheet. The surface contact that existed between the work piece and the drill served as the basis for the mathematical modeling of torque and axial force. The findings of the FEA simulation and the experiments were found to be in good agreement.

2 Materials and Methods

2.1 Materials

A thick sheet of the industrial steel alloy EN-24 that was 50 mm × 50 mm × 12 mm in size served as the work piece in the current set of studies. This industrial alloy is a hot-worked, special version of EN-24 that has good hardness and abrasion resistance properties. The seller who provided the test sample was able to ascertain the chemical makeup of this product, and that data is included in Table 1.

Table 1 Chemical composition of industrial alloy EN-24 (Kannan et al. [15])

C	Si	Mn	S	P	Cr	Mo	Ni
0.36–0.44	0.10–0.35	0.45–0.70	0.040	0.035	1.00–1.40	0.20–0.35	1.30–1.70

2.2 Experimental Setup

The trials are performed on a vertical CNC-drilling machine (MAXIMILL MTAB) manufactured by Batliboi Machine Tools Ltd. and installed in the advanced manufacturing laboratory of the Mechanical Engineering Department at CIPET in Jaipur (Rajasthan, India). The pictorial view of the CNC-drilling machine shown in Fig. 1 having the following specifications as shown in Table 2

The industrial alloy EN-24 plate of 100 mm x 100 mm × 12 mm size is mounted on the Wire EDM machine and four specimens of 50mmx50mm size were cut which were mounted on CNC Drilling to perform the experiments as shown in Fig. 2a. Due of its convenience and simplicity, a 50 mm × 50 mm × 12 mm square cut was chosen for this study. The cut is made beginning at the edge of the working piece, as depicted in Fig. 2b. Center to center distance of the hole is 32 mm for each hole. A flat end drill was used during the drilling operation and 6 mm diameter holes were cut. The TWR measurements in micrometer were carried out three times using Mitutoyo's surf tester, a portable TWR tester; the average result was taken into account as the TWR value for the purpose of analysis (Table 2).

The trials' levels and contributing factors are calculated using Taguchi's method. The nominal MRR and best TWR have been determined using the following formulas after all trials have been completed using the data from MINITAB software of L16 OA.

Fig. 1 Pictorial view and cutting operation on CNC drilling machine

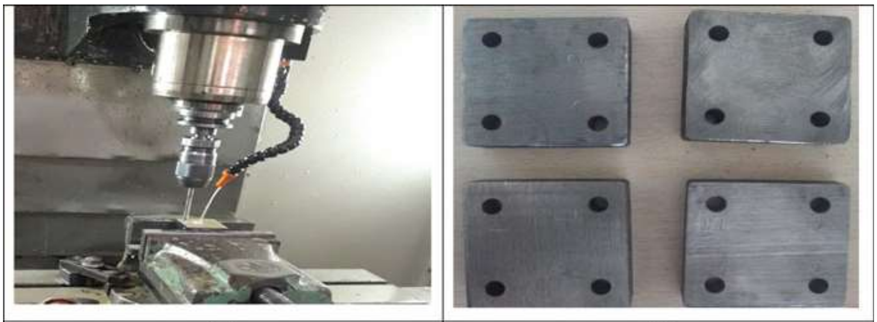

Fig. 2 Working zone and specimens of work material after drilling

Table 2 Specification of CNC-drilling machine (MAXMILL MTAB)

Sr. No	Description	Specification
01	Travel (mm × mm × mm)	640 × 600 × 500
02	Clamping area (mm × mm)	850 × 600
03	Spindle speed (rpm)	8000
04	Spindle motor (kW)	5.5/7.5
05	Maximum loading capacity (kg)	500
06	Air source (bar)	6–8
07	Machine net weight (kg)	3000
08	Power requirement (kVA)	15
09	Tool magazine (No. of tools)	30
10	Max. tool dia. /weight (mm/kg)	100/7
11	Position accuracy XYZ (microns)	0.8 × 2 × 2

2.3 *Selection of Levels*

The levels and components of the process parameters, by which the machining processes are carried out, are shown in Table 3.

Table 3 Factors and levels for CNC drilling operation

Designation	Factors	Level			
		I	II	III	IV
A	Feed (mm/min)	10	11	12	13
B	Spindle speed (RPM)	800	900	1000	1100
C	DOC (mm)	1.0	1.25	1.50	1.75

3 Results and Discussions

This section uses Taguchi's technique to calculate the experimental findings for optimal TWR using three unique process parameters: feed, spindle speed, and depth of cut. The results are shown in Table 4.

3.1 Effects on TWR

The S/N ratio for TWR Smaller is better option is selected because TWR should be reduced to improve productivity of the machine of the CNC drilling process. The **equation for** calculating S/N ratios for "smaller is better"

Smaller is Better:

$$\left(\frac{S}{N}\right)_{LB} = -10\log(MSD)_{LB}$$

where

Table 4 Experimental results of TWR

S.No	A: Feed (mm/min)	B: Speed (RPM)	C: Depth of cut (mm)	TWR (gm)
1	1	1	1	0.0037
2	1	2	2	0.0034
3	1	3	3	0.0030
4	1	4	4	0.0027
5	2	1	2	0.0033
6	2	2	1	0.0031
7	2	3	4	0.0029
8	2	4	3	0.0026
9	3	1	3	0.0033
10	3	2	4	0.0031
11	3	3	1	0.0028
12	3	4	2	0.0025
13	4	1	4	0.0032
14	4	2	3	0.0030
15	4	3	2	0.0028
16	4	4	1	0.0025

$$(MSD)_{LB} = \frac{1}{R}\sum_{j=1}^{R}\left(y_j^2\right)$$

S/N ratios for all 16 experiments are presented in Table 5 for the TWR response parameter.

The most interesting result from S/N ratio analysis is rank identification of factors for selective response variable. Tables 6 and 7 show the rank of factors for TWR using S/N ratio and raw data analysis. The depth of the cut is the most ranked factor among other factors for response variable TWR. The least ranked factors are spindle speed, the reason behind this task is the narrow range of the spindle speed.

Table 5 S/N ratio analysis for TWR

S. No	A: Feed (mm/min)	B: Speed (RPM)	C: Depth of cut (mm)	TWR (gm)	S/N ratio
1	1	1	1	0.0037	48.6360
2	1	2	2	0.0034	49.3704
3	1	3	3	0.0030	50.4576
4	1	4	4	0.0027	51.3727
5	2	1	2	0.0033	49.6297
6	2	2	1	0.0031	50.1728
7	2	3	4	0.0029	50.7520
8	2	4	3	0.0026	51.7005
9	3	1	3	0.0033	49.6297
10	3	2	4	0.0031	50.1728
11	3	3	1	0.0028	51.0568
12	3	4	2	0.0025	52.0412
13	4	1	4	0.0032	49.8970
14	4	2	3	0.0030	50.4576
15	4	3	2	0.0028	51.0568
16	4	4	1	0.0025	52.0412

Table 6 Rank identification of factors for response TWR "**S/N ratio**"

Level	A	B	C
1	49.96	49.45	50.48
2	50.56	50.04	50.52
3	50.73	50.83	50.56
4	50.86	51.79	50.55
Delta	0.9	2.34	0.08
Rank	**2**	**1**	**3**

Table 7 Rank identification of factors for response TWR "**Raw data option**"

Level	A	B	C
1	0.0032	0.003375	0.003025
2	0.002975	0.00315	0.003
3	0.002925	0.002875	0.002975
4	0.002875	0.002575	0.002975
Delta	0.000325	0.0008	0.00005
Rank	**2**	**1**	**3**

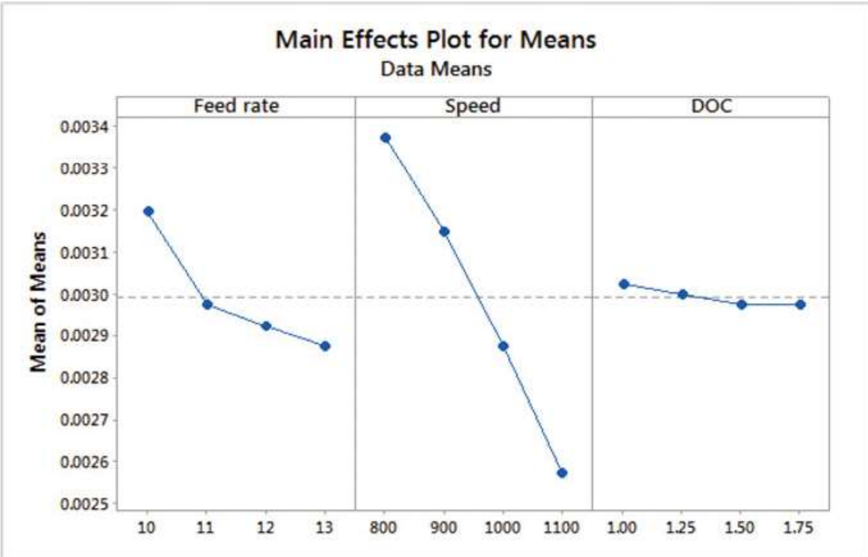

Fig. 3 Main effect plots for response TWR "raw"

In both cases either S/N ratio and raw data analysis results are the same of rank identification for response TWR. Figures 3 and 4 show the effect of factors on response TWR in a graphical manner.

3.2 Interaction Plots for TWR

These plots are generated among two factors for selective response to show interaction among them. Full matrix interaction plot for TWR is presented in Fig. 5 that shows the full scale interaction plots for all three input parameters with response parameter TWR.

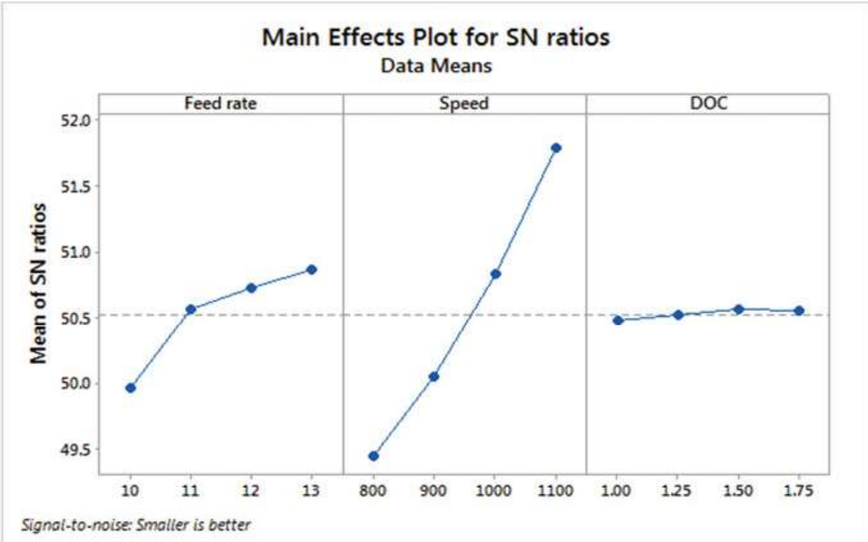

Fig. 4 Main effect plots for response TWR "S/N ratio"

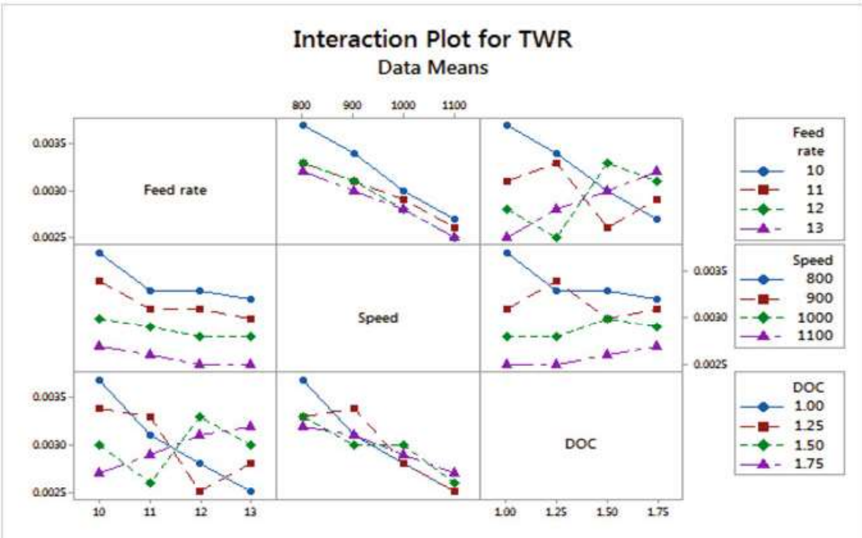

Fig. 5 Full scale interaction plot for TWR

Table 8 Optimal solution for both responses

Response	A	B	C
TWR	4	4	3

3.3 Optimal Solution Prediction

After completing the ranking of the selective replies, the next step is to determine the ideal ranking of the amounts of variables for both of the responses, which are shown in Table 8. The results are reported in a coded value according to the Taguchi method of the DOE approach. The maximum values in rank identification table are considered as optimum levels of each factor for TWR. For response TWR, maximum values (S/N ratio Analysis) for factors A(feed), B(speed) and C(DOC) are at level 4, level 4 and level 3 respectively.

3.4 Estimation of Optimal Solution

As can be seen in Table 8, the top levels for both responses have been generated; the next step is to determine the estimated values of the responses so that they may be verified. Within this section, the Roy estimate technique is utilized in order to do this assignment.

3.5 Estimation of Optimum Response Characteristics for TWR

$$\mu_{TWR} = \overline{A}_4 + \overline{B}_4 + \overline{C}_3 - 2TWR$$

where

TWR is average of TWR = 0.00299.

A_4 represents mean value of factor A for level 4 which is = 0.0028.

B_4 represents mean value of factor B for level 4 which is = 0.0025.

C_3 represents mean value of factor C for level 3 which is = 0.0029.

Substituting the values of A, B, C and TWR in the above equation,

$$\mu_{TWR} = 0.0028 + 0.0025 + 0.0029 - 2 * 0.0031 = 0.0020$$

Using the Equations, one can determine the confidence intervals for the population (CI_{POP}) and the confirmation experiments (CI_{CE}) at a level of 95%.

$$CI_{CE} = \sqrt{F_{\alpha}}(1,\, f_e)V_e\left[\frac{1}{n_{eff}} + \frac{1}{R}\right]$$

And

$$CI_{POP} = \sqrt{\frac{F_{\alpha}(1,\, f_e)V_e}{n_{eff}}}$$

where, F_{α} $(1,\, f_e)$ = The F ratio against DOF 1 and error degree of freedom (f_e) at the confidence level of $(1 - \alpha)$.

$$n_{eff} = \frac{N}{1 + [\text{DOF associated in the estimate of mean response}]}$$

$$\eta_{eff} = \frac{16}{1+3} = 4$$

R = Sample size for confirmation experiments = 1.
V_e = Error variance = 0.00001.
f_e = error DOF = 12.
$F_{0.05}$ (1, 12) = 4.
Substitute all values in formulas

$$CI_{CE} = \sqrt{F_{0.05}(1,\, 12) * V_e * \left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} = \sqrt{4.75 * 0.0001 * \left[\frac{1}{4} + \frac{1}{1}\right]} = \pm 0.00012$$

$$CI_{POP} = \sqrt{\frac{F_{0.05}(1,\, 12) * V_e}{n_{eff}}} = \sqrt{\frac{4.75 * 0.0001}{4}} = \pm 0.000177$$

The estimated confidence interval for confirmation experiments is as follows:

$$Mean\mu_{TWR} - CI_{CE} < \mu_{TWR} < Mean\mu_{TWR} + CI_{CE}$$

$$= 0.00124 < \mu_{TWR} < 0.00324$$

Confidence interval for the entire population at 95% level is (Table 9):

$$Mean\mu_{TWR} - CI_{POP} < \mu_{TWR} < Mean\mu_{TWR} + CI_{POP}$$

$$= 0.0026 < \mu_{TWR} < 0.00331$$

ANOVA analyses for TWR after the elimination of insignificant terms have been presented in the Table 9.

Table 9 ANOVA for TWR

Source	DF	Seq. SS	Contribution	Adj. SS	Adj. MS		F-value	P-value
Model	3	0.000002	95.26%	0.000002	0.000001		80.36	0
Linear	3	0.000002	95.26%	0.000002	0.000001		80.36	0
Feed rate	1	0	12.15%	0	0		30.75	0
Speed	1	0.000001	82.75%	0.000001	0.000001		209.43	0
DOC	1	0	0.35%	0	0.00001		0.9	0.362
Error	12	0	4.74%	0	0.00001			
Total	15	0.000002	100.00%					

Table 10 Confirmation of TWR results

Response parameter	Optimal set of parameters	Predicted optimal value	Predicted confidence intervals at 95% confidence level	Experimental value
TWR	$A_4B_4C_3$	0.0020	CI_{POP}: 0.0026 < μ_{TWR} < 0.0033 CI_{CE}: 0.00124 < μ_{TWR} < 0.00324	0.0023

3.6 Confirmation of Experiment for TWR

Final result (Table 10) confirms the validity of the trials by displaying the predicted and experimental values of the optimal solution's TWR response range. A TWR authorization is granted in this instance.

4 Conclusion

The preceding discussions make it abundantly evident that the TWR (0.0023 gm) that is optimal can be attained at A4, B4, and C3 respectively. It has been determined, after a large number of calculations and analyses for optimum TWR, that the optimum TWR value for the EN24 tool steel can be attained by using the DOE to experiment with varying the different levels of input parameters such as speed, feed rate, and depth of cut. This has led to the formulation of the following conclusion: Therefore, the conclusion that can be drawn from this body of work is that the three process parameters at levels 4, 4, and 3 contribute equally to the ideal value of TWR (feed 13 mm/min, speed 1100 rpm and depth of cut 1.50 mm). According to the results of an analysis of variance (ANOVA), the speed is the most influential factor in determining the TWR, accounting for 82.75% of the total variance. The feed rate came in second, accounting for just 12.15%. Nonetheless, it is generally accepted that the depth of cut is the most important factor in determining the TWR.

Acknowledgements The authors would like to extend their gratitude to CIPET, Jaipur for providing the CNC drilling machine (MAXMILL MTAB) that was used to evaluate the tool wear rate of EN-24 steel plates having input variables feed, speed and depth of cut.

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