Journal of the Brazilian Society of Mechanical Sciences and Engineering (2018) 40:370
https://doi.org/10.1007/s40430-018-1245-y

TECHNICAL PAPER

Optimisation of drilling parameters on St37 based on Taguchi method

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Received: 6 May 2017 / Accepted: 23 May 2018 / Published online: 10 July 2018

Abstract

Today, machining processes have become one of the most widely used methods in extensive production parts and drilling is one of the widely used machining processes in manufacturing. Almost 25% of the average time of machining process is for drilling. As a result, drilling during the production process is a bottleneck, and this is very evident in silos companies. Some difficulties associated with drilling in these companies are substantial problems, and they try to optimise their process. In this regard, the drilling process and its impact parameters are determined. By examining the factors and levels of machine and twist drill, the experimental design is done, and some factors such as spindle speed, feed rate, point angle, and clearance angle are taken into account. So, Taguchi method is performed and their results are analysed by signal-to-noise criterion, response surface method, and analysis of variances. According to some studies, two quantities of force and torque are considered as the output of the process simultaneously. Finally, by using signal-to-noise ratio (SNR) analysis, the optimum amounts of torque are determined for spindle speed, feed rate, point angle and clearance angle as is 320 rpm, 0.13 mm/min, 128° and 10°, respectively, and optimum amounts for force module are calculated as the previous values, while the point and clearance angles have been changed to 118° and 14°, respectively.

Keywords Optimisation · Drilling · Thrust force · Torque · Taguchi method · RSM · ANOVA

1 Introduction

Metal cutting operations including drilling, turning, and milling are widely used in manufacturing to produce a variety of mechanical components. Drilling is one of the most widely used processes in manufacturing [1]. Conventional drilling with twist drill is one of the most economical and efficient machining processes for hole making as well as for riveting and fastening structural assemblies in the aerospace and automotive industries. Optimising the cutting parameters of drilling such as tool geometry and a machine can be helpful the productivity, which is influenced by cutting thrust and torque [2–4]. Some parameters in drilling such as cutting speed, feed rate, and helix angle greatly affect the performance measures such as thrust force and torque [5–9]. Kıvak et al. [10] worked on the optimisation of drilling parameters using the Taguchi technique to obtain minimum surface roughness and thrust force. The cutting tool, cutting speed, and the feed rate were selected as control factors. As a result of experimental trials performed using the Taguchi orthogonal array, it was found that the cutting tool was the most significant factor affecting the surface roughness and feed rate was significantly affected by thrust force. Jalali and Kolarik [11] worked on tool life and machinability models for drilling steels. Results of the experiments are as follows: cutting speed, feed, and hardness of steel have a significant impact on tool life. With increasing cutting speed, feed rate, and hardness, tool life is reduced. Torque is increased due to lack of cutting edge sharp. With increasing cutting speed and hardness, torque increases; torque is greatly increased while feed and diameter increase. The increase in cutting speed and diameter causes the more thrust force, and thrust force is strongly increased while feed and hardness increase. Strenkowski et al. [5] investigated an analytical finite element technique for predicting thrust force and torque in drilling. Clearance angle 10° and 6 levels for

Technical Editor: Márcio Bacci da Silva.

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helix angle were defined. According to the results, the AISI 1020 needs larger helix angle which reduces the thrust force and torque. Paul et al. [12] worked on tip drills and showed that optimum thrust force and torque occur when the tip of the drill with conical one to be used. Kurt et al. [7] used the application of Taguchi methods in the optimisation of cutting parameters for surface finish and hole diameter accuracy in dry drilling processes. Some parameters such as cutting speed, feed rate, depth of cut, and drilling tool were input, and surface roughness and precision drilling diameter were adopted as output process. The tests were carried out on aluminium alloy 2024 under dry conditions. The results showed that the greatest impact on the output is feed rate. Isbilir and Ghassemieh [13] worked on finite element analysis of drilling of titanium alloy. The results imply that increased feed rate and cutting speed are increased torque and thrust force. Consequently, to optimise torque and thrust force, feed rate and cutting speed must be reduced. Prasanna et al. optimised the process parameters of small hole dry drilling in Ti–6Al–4V by using Taguchi and grey relational analysis. Holes were machined in a Ti–6Al–4V plate of 0.4 mm thickness using twisted carbide drill bits of 0.4 mm diameter. The result indicates that thrust force is decreased with increasing feed rate [14]. Neseli [15] studied on optimisation of process parameters with minimum thrust force and torque in drilling operation using Taguchi method. The drilling parameters which evaluated were cutting speed, feed rate, and helix angle. The result showed that the feed rate is the most significant factor affecting the thrust force, while the cutting speed contributes the most to the torque. Chaudhary et al. [16] used response surface methodology for optimisation of drilling parameters of hybrid metal matrix composites. Input parameters include spindle speed, feed rate, and point angle, and output parameters include material removal rates and surface finish. They concluded that the better surface finish and MRR needs the more spindle speed and the less feed rate and point angle. They did not reach a comprehensive view of the most effective parameters for the optimal process. Chatterjee et al. [17] studied the effect of drilling parameters in AISI 304 stainless steel using NSGA-II approach. They chose spindle speed, feed rate, and drill diameter among the many factors of the drilling parameters. The circularity of hole and burr height was defined as the output of the process. Analysis of variance showed that spindle speed significantly effects on circularity of hole, since all parameters such as spindle speed, feed rate, and drill diameter effect on the burr height. Cicek et al. [18] optimised the drilling parameters on AISI 304 stainless steel using Taguchi technique and response surface method. In the experiments, the behaviour of cryogenic tools and dry conditions is considered. A cutting tool, cutting speed and feed rate are input, and surface roughness and roundness error are considered as output. The results of a signal-to-noise ratio and response surface show that feed rate and cutting speed have the greatest impact on surface roughness and roundness error. An optimisation machining procedure on Al 6351 using genetic algorithm is investigated by Santhanakrishnan et al. [19].

In this paper, four machining parameters include spindle speed, feed rate, point angle, and clearance angle are examined to investigate the optimised level for each parameter to achieve the minimum load and torque. In the second section of this research, a workpiece based on St37 is employed to test the drilling experiments. An electrical load cell set-up is used to monitor the normal load and torques during the time. To examine efficiently, in the third section, an orthogonal array based on Taguchi method is designed. Analytic tools like SNR and ANOVA are used in Sect. 4, to interpret the results meaningfully. Two regression models are generated from these experiments and show how the parameters in a matching process can be effective in minimising the energy.

2 Experimental methods

In this study, St37 (structural steel) was used as the workpiece. The dimensions of the workpiece were 75*50*40 mm^3. The drilling experiments were examined by a radial machine (Z3050*16(I)) which is shown in Fig. 1.

The HSS twist drill was used with 33 mm in diameter at four different point and clearance angles, and helix angle is 25°. Figure 2 shows the conceptual shape of HSS twist drill.

All drilling experiments were conducted under soap-water conditions.

2.1 Thrust force and torque measurement

In the drilling experiments, a load–torque cell, model LF-201, was used for the measurement of the thrust force and torque up to 23 KN and 200 Nm in a row. Measuring and showing thrust force and load at the same time is one of the advantages of this device. The signals of strain gauges of thrust force and torque were transmitted to two indicators which one of them is shown thrust force and another is shown torque. For recording data and knowing the speed of transforming it, a software is made and we have all these things on a personal computer. The workpiece and device and fixture were firmly fixed to each other. Then, they were fixed on the table of the machine. The experimental set-up for thrust force and torque measurement is shown in Fig. 3.

Fig. 1 Radial machine used in one of the industrial factories in Mashhad

Components of the cutting forces occurred during the drilling process, namely main cutting force (F_c), thrust force (F_t) and radial force (F_r) are shown in Fig. 4. The force F_r acting on both cutting edges is considered to counterbalance each other. Hence, the forces F_c and F_t only are effective in drill process [10]. On the other hand, torque can be calculated as (1).

$$T = F_c \frac{D}{4} \tag{1}$$

3 Design of experiments

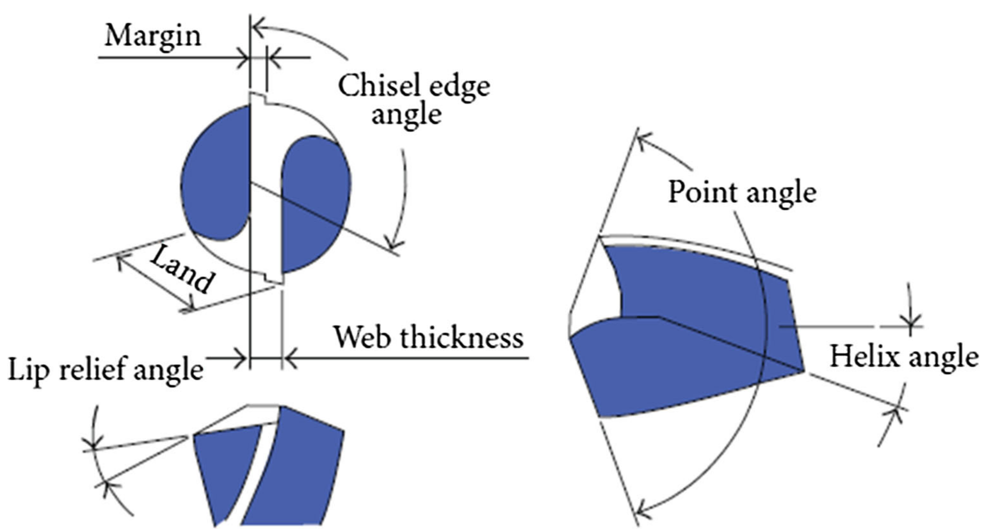
Traditional experimental design procedures are too complicated and cost too much. A large number of experimental works have to be performed when the number of process parameters increases. To solve this problem, Taguchi method was used by utilising of orthogonal arrays to study the entire parameter space with only a small number of experiments [20–22]. The best advantage of this method is the saving of effort in conducting experiments, saving experimental time, reducing the cost, and discovering more affecting factors quickly. The RSM is a collection of mathematical and statistical techniques which is useful for the modelling and analysis of problems. This is why response surface method is used for better analysing [23]. In this study, spindle speed (N), feed rate (F), point angle (Pa), and clearance angle (Ca) were selected as control factors for thrust force and torque values, and their levels were determined as shown in Table 1.

In this study, 4 factors and 4 levels were determined. Taguchi is suggested L16. The experimental design consists of 16 trials which are shown in Table 2 and Fig. 5, respectively, with the output of the process.

4 Results and discussion

The Taguchi method uses S/N ratio to measure the variations of the experimental design. The equation of smaller-better was selected which shows in (2) [24].

Fig. 2 Geometry of twist drill



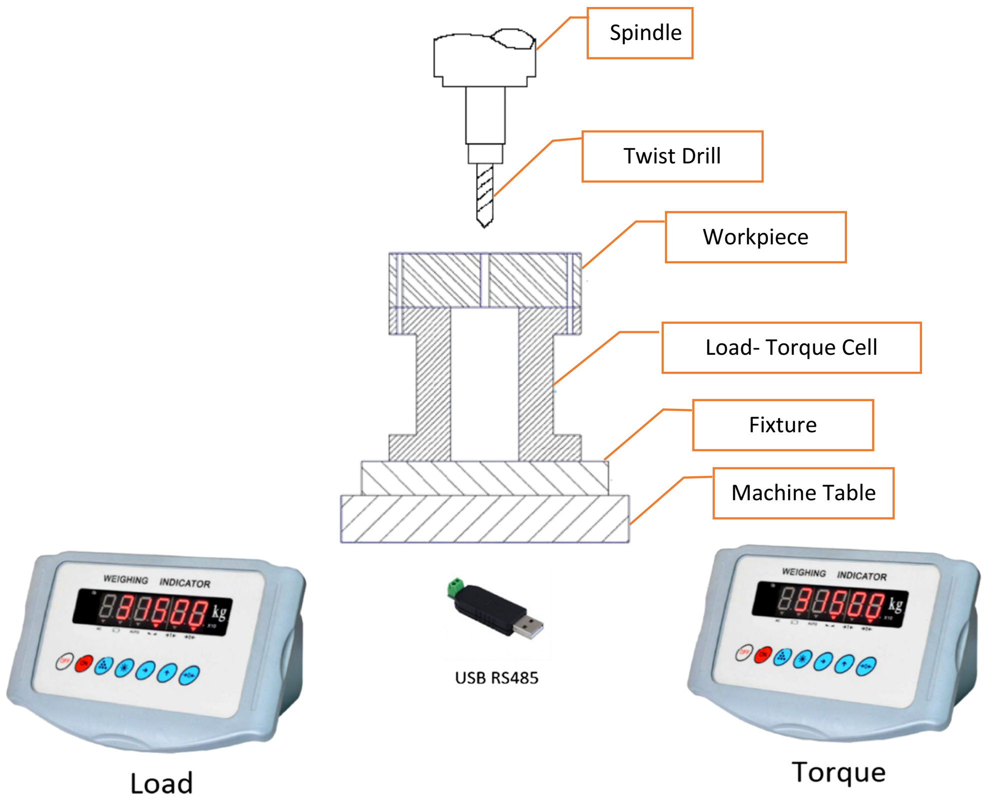


Fig. 3 Chart of experiments set-up

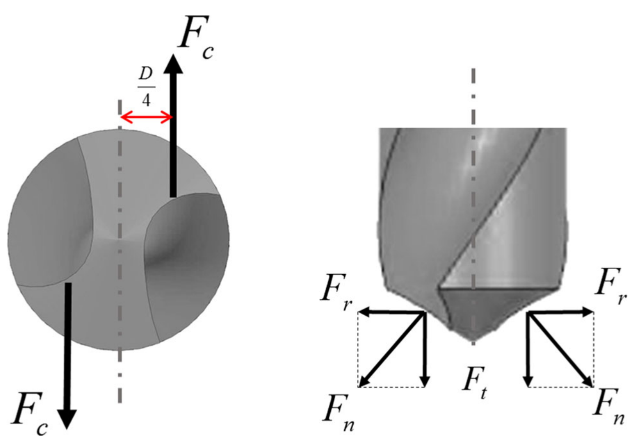


Fig. 4 Forces acting on a drill

Table 1 Experimental design using *L*16 and their responses

Factor	Level 1	Level 2	Level 3	Level 4
Spindle speed (*N*), rpm	160	200	250	320
Feed rate (*F*), mm/min	0.13	0.16	0.2	0.25
Point angle (Pa), °	108	118	128	138
Cutting angle (Ca), °	8	10	12	14

Table 2 Experimental design using *L*16 and their responses

Exp. number	*N* (rpm)	*F* (m/min)	Pa (°)	Ca (°)	Thrust force (N)	Torque (Nm)
1	160	0.13	108	8	287.5	60.7
2	160	0.16	118	10	256	55.9
3	160	0.2	128	12	263.6	67.8
4	160	0.25	138	14	464.3	99.3
5	200	0.13	118	12	158	46.8
6	200	0.16	108	14	224.3	57
7	200	0.2	138	8	264	68.9
8	200	0.25	128	10	338.9	76.2
9	250	0.13	128	14	125.5	44.3
10	250	0.16	138	12	251.2	60.9
11	250	0.2	108	10	285.7	65
12	250	0.25	118	8	387.3	74.4
13	320	0.13	138	10	220.4	47.2
14	320	0.16	128	8	230.7	53
15	320	0.2	118	14	131.3	64.6
16	320	0.25	108	12	322	80.3

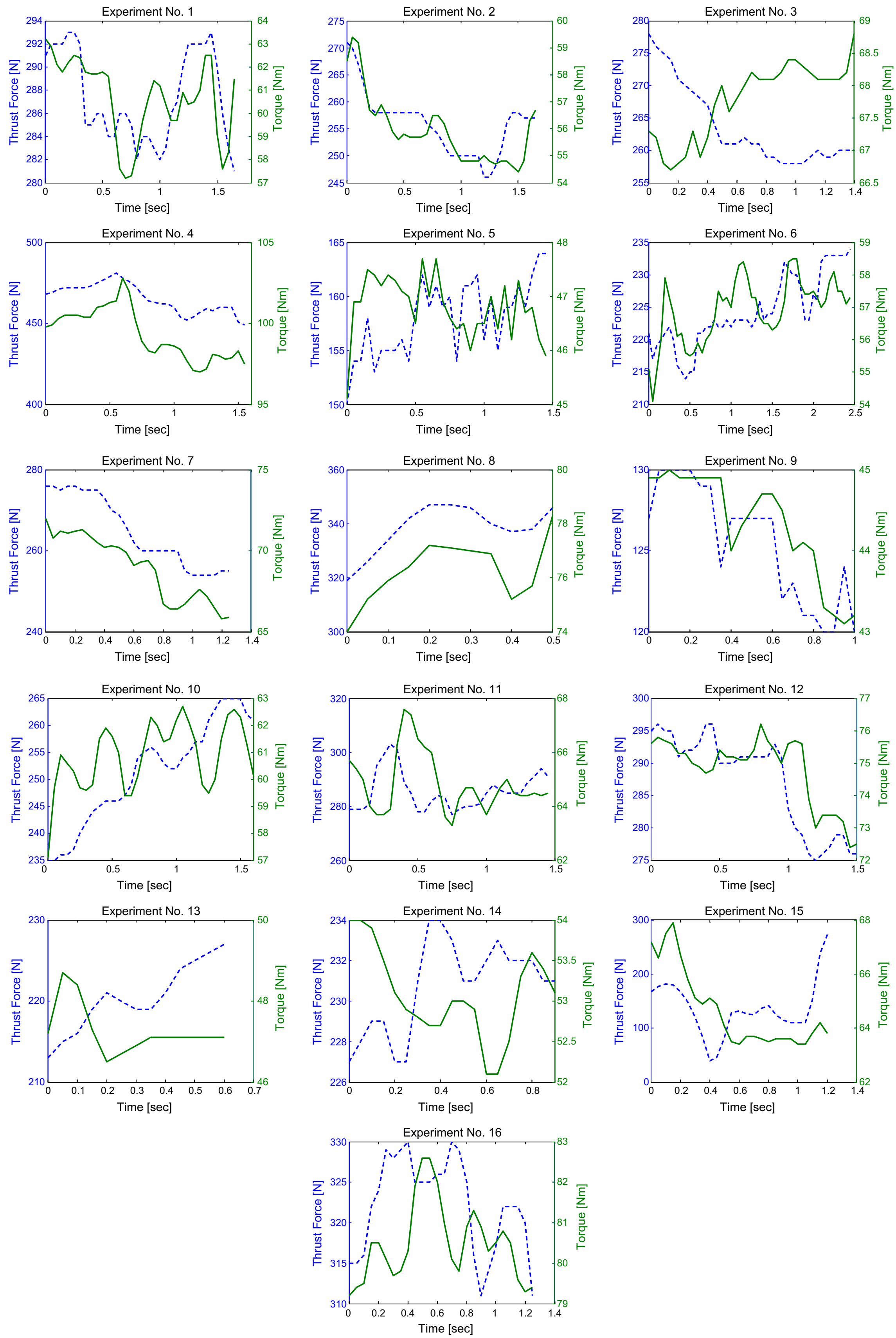


Fig. 5 All of 16 experiments examined for torque and load

Table 3 Response of signal-to-noise ratios for trust force, criterion: smaller is better

Level	*N*	*F*	Pa	Ca
1	− 49.77	− 45.50	− 48.87	− 48.51
2	− 47.51	− 47.61	− 45.92	− 48.69
3	− 47.06	− 47.08	− 47.06	− 47.64
4	− 46.66	− 50.82	− 49.16	− 46.17
Delta	3.11	5.32	3.24	2.51
Rank	3	1	2	4

Table 4 Response of signal-to-noise ratios for torque, criterion: smaller is better

Level	*N*	*F*	Pa	Ca
1	− 36.80	− 33.87	− 36.28	− 36.09
2	− 35.73	− 35.06	− 35.50	− 35.59
3	− 35.58	− 36.47	− 35.42	− 35.96
4	− 35.57	− 38.28	− 36.47	− 36.05
Delta	1.23	4.41	1.05	0.50
Rank	2	1	3	4

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

For the calculation of *S*/*N* ratio, since the lowest value of thrust force and torque was the desired outcome for high product quality. *S*/*N* ratios of thrust force are shown in Table 3 and Fig. 6, respectively.

S/*N* ratios of torque are shown in Table 4 and Fig. 7, respectively.

Analysis of variance will be the significant statistical method used to interpret experimental data and make the necessary decisions. In this study, ANOVA is used to analyse the effects of spindle speed, feed rate, point angle, and clearance angle on thrust force and torque. The ANOVA results are illustrated for thrust force and torque in Tables 5 and 6, respectively. Both of them illustrate that feed rate is a more effective parameter in thrust force and torque due to the minimum value for its *p* value. In other hand, point angle is not as effective as other parameters.

Presenting the effective parameters may help the machining process, but introducing a proper mathematical model can be used efficiently as a predictor to find the best accurate value for each machining parameters or achieving the minimum value of load and torque. For this reason, two linear models and full quadratic modes are used to show how a model can predict load and torque of a machining process. Tables 7 and 8 describe the linear and quadratic models of response surface method for thrust force, respectively. To show how these models can be successful in predicting, the coefficient of determination is used. As shown, this coefficient in the quadratic model is 88.50 and 96.99% for thrust force and torque, respectively, which is more accurate than the linear model.

Two contours of the full quadratic model are shown in Figs. 8 and 9 for thrust force and torque, respectively. This

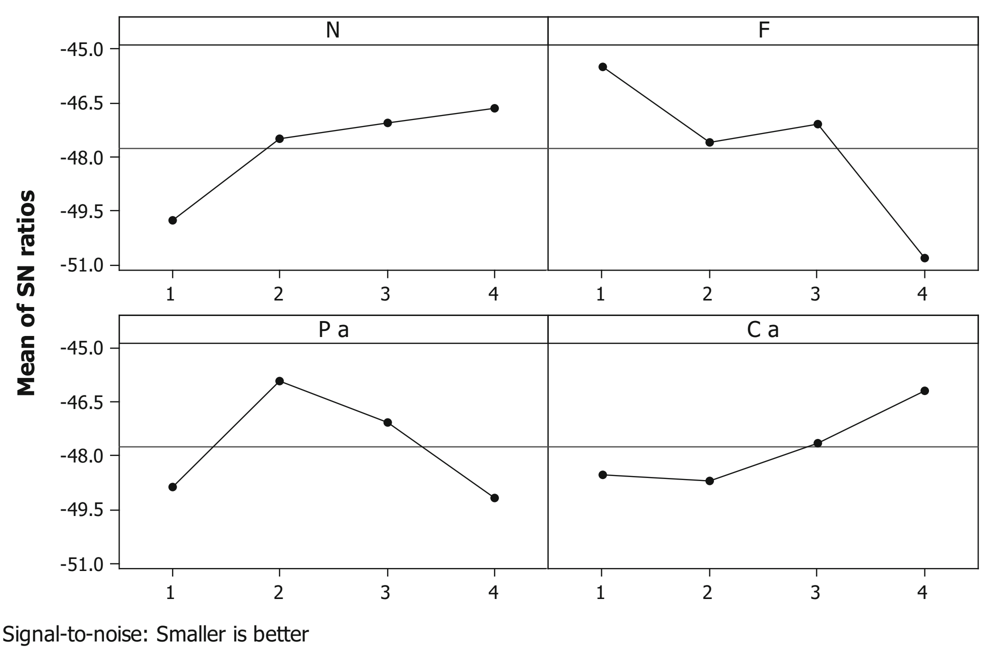


Fig. 6 Signal-to-noise ratios for trust force, criterion: smaller is better

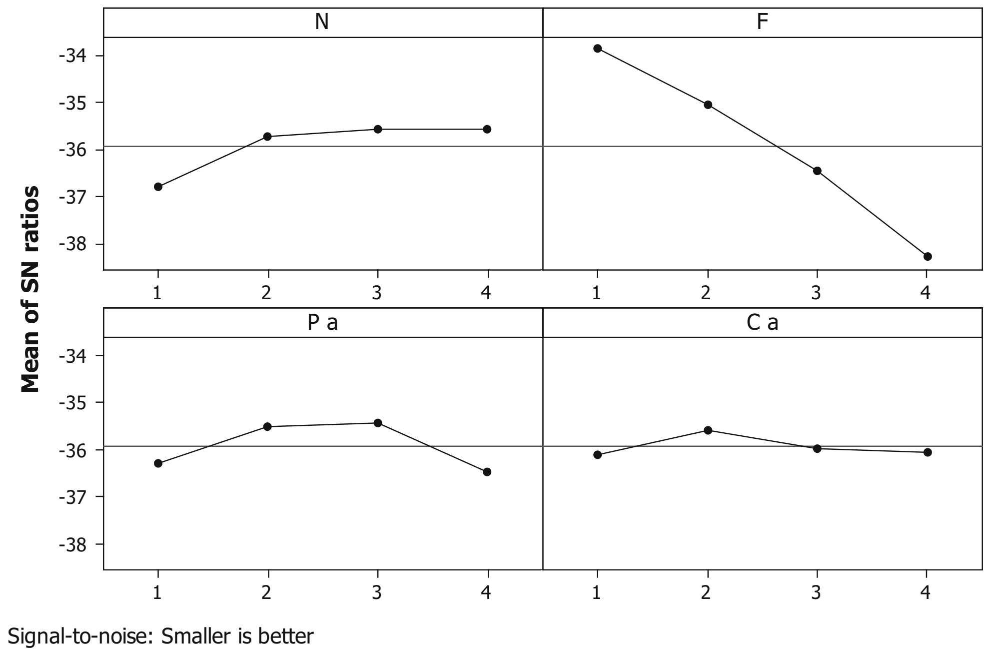


Fig. 7 Signal-to-noise ratios for torque, criterion: smaller is better

Table 5 ANOVA table for thrust force

Source	*DF*	Seq SS	Adj SS	Adj MS	*F*	*P*
N	1	16,140	16,140	16,140	4.50	0.057
F	1	42,601	42,601	42,601	11.88	0.005
Pa	1	1687	1687	1687	0.47	0.507
Ca	1	2860	2860	2860	0.80	0.391
Error	11	39,430	39,430	3585		
Total	15	102,718				

Table 6 ANOVA table for torque

Source	*DF*	Seq SS	Adj SS	Adj MS	*F*	*P*
N	1	181.04	181.04	181.04	4.24	0.064
F	1	2346.67	2346.67	2346.67	55.02	0.000
Pa	1	19.96	19.96	19.96	0.47	0.508
Ca	1	16.27	16.27	16.27	0.38	0.549
Error	11	469.16	469.16	42.65		
Total	15	3033.09				

figure shows how different values of the most effective parameters (spindle speed and feed rate) can change the force and torque in a machining process. Finding the optimum value for each parameter to achieve the minimum thrust force and torque value is a challenge. To obtain them, a multi-objective optimisation algorithm based on

Table 7 Proposed linear models for thrust force and torque

Term	Thrust force $R^2 = 61.61\%$	Torque $R^2 = 84.53\%$
Constant	219.50	39.601
N	− 28.41	− 3.009
F	46.15	10.832
Pa	9.18	0.999
Ca	− 11.96	0.902

Table 8 Full quadratic model for thrust force

Term	Thrust force $R^2 = 88.50\%$	Torque $R^2 = 96.99\%$
Constant	1239.33	642.782
N	− 3.18	− 0.475
F	617.98	43.545
Pa	− 5.53	− 8.525
Ca	− 78.60	− 7.126
*N***N*	0	0.001
*F***F*	0	601.001
Pa*Pa	0	0.035
Ca*Ca	0	0.344
*N**Pa	0.03	0
*N**Ca	− 0.17	0
*F**Pa	− 30.26	0
*F**Ca	346.69	0
Pa*Ca	0.42	0

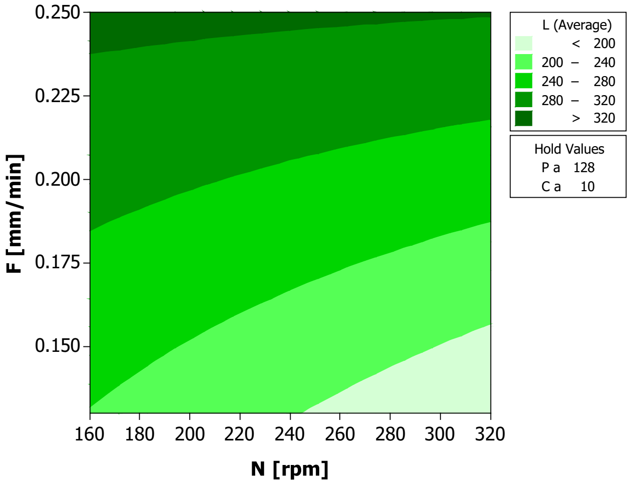


Fig. 8 Contour of thrust force in machining process versus feed rate (*F*) and spindle speed (*N*)

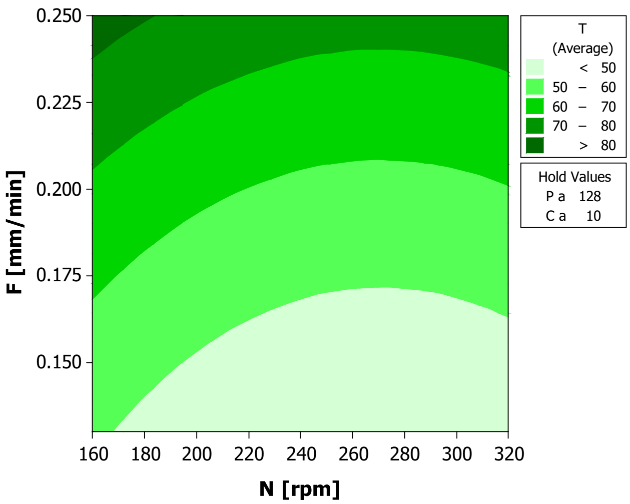


Fig. 9 Contour of torque in machining process versus feed rate (*F*) and spindle speed (*N*)

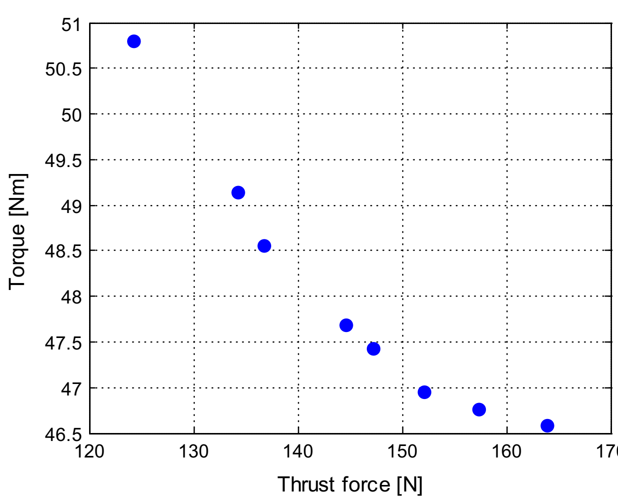


Fig. 10 Pareto front achieved by genetic algorithm

Table 9 Pareto front results (optimised objective functions and parameters)

	Thrust force	Torque	Spindle speed	Feed rate
1	163.8145	46.59409	237.4738	0.125024
2	152.1282	46.9609	256.5522	0.125043
3	134.1787	49.14122	286.8662	0.125591
4	136.7633	48.56512	281.7141	0.125107
5	124.1961	50.79785	302.2078	0.12511
6	124.1961	50.79785	302.2078	0.12511
7	144.5591	47.69056	269.5246	0.125389
8	157.3022	46.76571	248.5304	0.125281
9	147.1852	47.43756	265.2567	0.1254
10	163.8145	46.59409	237.4738	0.125024
11	159.4487	46.64815	244.6179	0.125041

genetic is considered. The result in Fig. 10 shows a Pareto front diagram which indicates how two objective functions (thrust force and torque) can be minimised simultaneously. Also, optimised parameters are show in Table 9.

5 Discussion and conclusion

In this study, minimising the energy in machining process was considered. Thrust force and torque are two major parameters in this process which change energy consumption during the process. To measure the thrust force and torque in a machining process, an electrical set-up is employed to monitor the force and torque value during drilling process on a workpiece which was based on st37. Four parameters such as spindle speed, feed rate, point angle, and clearance angle are considered as parameters changing the thrust force and torque. Statistically designed experiments based on Taguchi methods were performed using *L*27 (4^4) orthogonal array to analyse the thrust force and torque as response variables, respectively. The results can be drawn as follows:

- The result of ANOVA indicates that the most significant factor affecting the thrust force and torque is the feed rate.
- The spindle speed level 4 (320 rpm), the feed rate level 1 (0.13 mm/min), the point angle level 2 (118°), and the clearance angle level 4 (14°) are the optimum cutting conditions to achieve low value of thrust force using the response table for *S*/*N* ratio.
- The spindle speed level 4 (320 rpm), the feed rate level 1 (0.13 mm/min), the point angle level 2 (128°), and the clearance angle level 2 (10°) are the optimum cutting conditions to achieve low value of torque using the response table for *S*/*N* ratio.

- Two quadratic models with high determination coefficient are presented to predict the thrust force and torque.
- As Figs. 8, 9 show, the white layers which addressed the minimum area of thrust force and torque simultaneously are considered by increasing spindle speed and decreasing feed rate. This outcome was investigated recently also by Taguchi method in Figs. 6, 7 where the highest values for SNR ratio described how load and torque can be minimised. Moreover, Pareto front by multi-objective genetic algorithm confirms the previous result and introduces a profile of values for spindle speed and feed rate to minimise the torque and thrust force based on the user's demand.

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