Trans Indian Inst Met (2018) 71(7):1615–1627
https://doi.org/10.1007/s12666-018-1296-x

TECHNICAL PAPER

Multi-performance Optimization of Drilling Carbon Fiber Reinforced Polymer Using Taguchi: Membership Function

K. Shunmugesh[1] · K. Panneerselvam[1]

Received: 28 September 2016 / Accepted: 6 March 2018 / Published online: 13 March 2018

Abstract The CFRP composite materials are widely used in aircraft, automobiles, infrastructures, 3D printing and many more areas where light weight and high strength is a major factor. This study outlines the implementation of Taguchi technique combined with the membership function to optimize the drilling process parameters using Taguchi L_{27} array with multiple performance characteristics to minimize the objective. The experiments were performed by using three drill bit types at three levels of cutting speeds and feed rates. The responses namely thrust force and torque were measured by using Kistler multi-component dynamometer 9257B; circularity and cylindricity were measured by using TESA micro-hite 3D Coordinated Measuring Machine (CMM). The drilling process parameters which directly influenced the performance characteristics were optimized using response surface methodology (RSM). The ANOVA (Analysis of Variance) results clearly indicated that the feed rate was the significant factor which affected the responses. The experimental values of S/N ratio were compared with predicted values of the membership function, and were found to be in good agreement with each other.

Keywords Carbon fiber reinforced polymer (CFRP) · Drilling · Taguchi · Response surface methodology · ANOVA · Membership function

✉ K. Panneerselvam
kps@nitt.edu

K. Shunmugesh
shunmugesh@gmail.com

[1] Department of Production Engineering, NIT, Trichy, India

1 Introduction

Now-a-days, for a variety of applications, the Fiber reinforced Plastics (FRP) composites materials are preferred in almost all the modern engineering industries because of their high strength to weight ratio. Carbon fiber reinforced polymer (CFRP) is said to be an excellent replacement for conventional materials with high strength and modulus. In addition to the strength and modulus, their fatigue properties are also excellent when compared to the well- known metallic structures. The CFRP is said to have extreme corrosion-resistant quality when mixed with proper resins. The CFRP composite materials are widely used in aircraft, automobiles, infrastructures, 3D printing and many more areas where light weight and high strength is a major factor. The CFRPs are very difficult to machining because of the arrangement of the fiber orientation and fiber reinforcement. The most commonly used machining process for all the engineering applications is drilling, which is used to fit the composite materials to the other structures of the system.

Prasanna et al. [1] developed a multi-performance optimization technique in dry drilling of Ti–6Al–4V using Taguchi Grey Relational Analysis (TGRA), which resulted in minimizing the thrust force by means of low feed rate and high spindle speed. Shanmughasundaram et al. [2] analysed the effect of feed rate, spindle speed and step angle in step drilling of Al–Si alloy–Gr composite using Taguchi and ANOVA. Their results revealed that feed rate is the most significant machining parameter which influences the thrust force. Chatterjee et al. [3] have reported the multi-objective optimization algorithm in drilling of AISI steel using NSGA-II (Non-dominated sorting genetic algorithm). The effectiveness of Pareto-optimal solution obtained by NSGA-II enhance the machining conditions.

Pandey et al. [4, 5] used grey relational analysis and fuzzy algorithm to optimize the multiple performance characteristics of bone drilling process and their results revealed that the feed rate is the most significant process parameter. Pinho et al. [6] studied the analysis of delamination at entry and exit of the CFRP laminate and evaluated the influence of feed rate and drill bit type. In their study, it is concluded that the diamond tools provide better results than the TiN/TiAlN coated drill bit types. Nasir et al. [7] reported their work on optimizing the residual tensile strength of the drilled flax fibre composite using Taguchi technique and concluded that the Feed rate has the significant effect on the residual tensile strength as well as delamination damage. Siddiquee et al. [8] employed Taguchi technique to optimize deep drilling parameters for minimizing the surface roughness of AISI 321 steel and concluded that the effectiveness of the approach minimizes the surface roughness. Rao and Padmanabhan [9] effectively formulated non-lienar regression models after conducting machining experiments using design of experiments and the factors are optimized using RSM. Kannan et al. [10] effectively used the neural network model for drilling copper and the results of the experiment revealed that the GA (Genetic Algorithm) and PSO (Particle Swarm Optimization) gives very good results in optimizing the responses. Abhishek et al. [11] examined the influence of feed, speed and drill diameter on thrust force and torque in drilling CFRP using TiAlN coated solid carbide drill bit using Harmony Search (HS) algorithm, GA and Taguchi technique. Their results revealed that the optimal parametric combination obtained by all three methodologies are same. Parthiban et al. [12] applied RSM for developing mathematical model laser cutting on AISI 316L sheet and reported that the reduced cubic model can reduce machining time and cost in manufacturing industries. Prakash et al. [13] utilized an L_{27} Taguchi orthogonal array with GRA (Grey Relational Analysis) and ANOVA to investigate the effect of feed rate, spindle speed and drill diameter in drilling MDF (Medium Density Fiber-board). Yang et al. [14] performed multi-objective optimization of zirconium coating using grey-fuzzy based Taguchi technique and the effective use of the technique increases the magnitude of the response variable. Khan et al. [15] investigated the effect of machining process using the Taguchi technique coupled with the GRA and found the degree of influence for each controllable process factor onto individual quality targets. Sahoo and Pradhan [16] optimized the process parameters in machining MMC (Metal Matrix Composites) using Taguchi technique and reported that the mathematical models for performance characteristics are found to be statistically significant. Gowda et al. [17] conducted drilling experiments on Al–Si_3N_4 metal matrix composite and investigated the effect of process parameters on circularity, cylindricity and surface roughness. They concluded that at high speed, circularity error increases and cylindricity increases with wobbling of drill bit.

Most of the optimization paper used the Taguchi technique only for single performance characteristics, but the real life and industry demands for multi-response optimization. The multi-response optimization was effectively achieved by many researches using Taguchi technique by combining with GRA, PCA, Fuzzy Logic, ANN etc. But the above process of combination with Taguchi technique only increased the complexity and computational process.

From the above literature review, it is evident that the multi-response optimization using the concept of weight for each and every response based on experiences and the end user expertise, is a difficult task and it increases the complexity of the proposed approach. Therefore in this paper an attempt has been made to optimize the multi-performance characteristics of drilling CFRP using Taguchi technique [18]. Based on experimental results to minimize the thrust force, torque, circularity and cylindricity, a membership function has been created to optimize the cutting speed, feed rate and drill bit type.

2 Materials and Methods

2.1 Work Piece and Drill Tool Materials

In this study, CFRP/Epoxy composite laminate manufactured by hand layup and auto clave were chosen as the work piece material for conducting drilling experiments. The work piece used for the experiments was CFRP (T300 Bi-directional Carbon Fibre and Two part Epoxy Resin). The carbon fiber used in the material was PAN-based and the average thickness of the carbon fabric was 0.25 mm. The size of the specimen used was 150 × 15 × 8 mm. The cutting tools used for the dry drilling were HSS drills (Miranda Tools India Ltd), Kennametal Solid Carbide Drill (TiAlN Black Coated-KC7325 Grade) and WIDIA Solid Carbide Drill (TiN Golden coated - WU25PD Grade).

2.2 Experimental Design

The experiments were carried out using BFW Ltd BMV 40T20 CNC vertical milling machine as shown in Fig. 1.

Three different drill tools were used to conduct the drilling experimental by varying the cutting speeds from 30 to 50 m/min and feed rates from 0.025 to 0.1 mm/rev. The experimental design is presented in Table 1.

Two trials of experiments were conducted and the averages of the responses were taken for optimization so as to minimize the variations in the experimental results. The

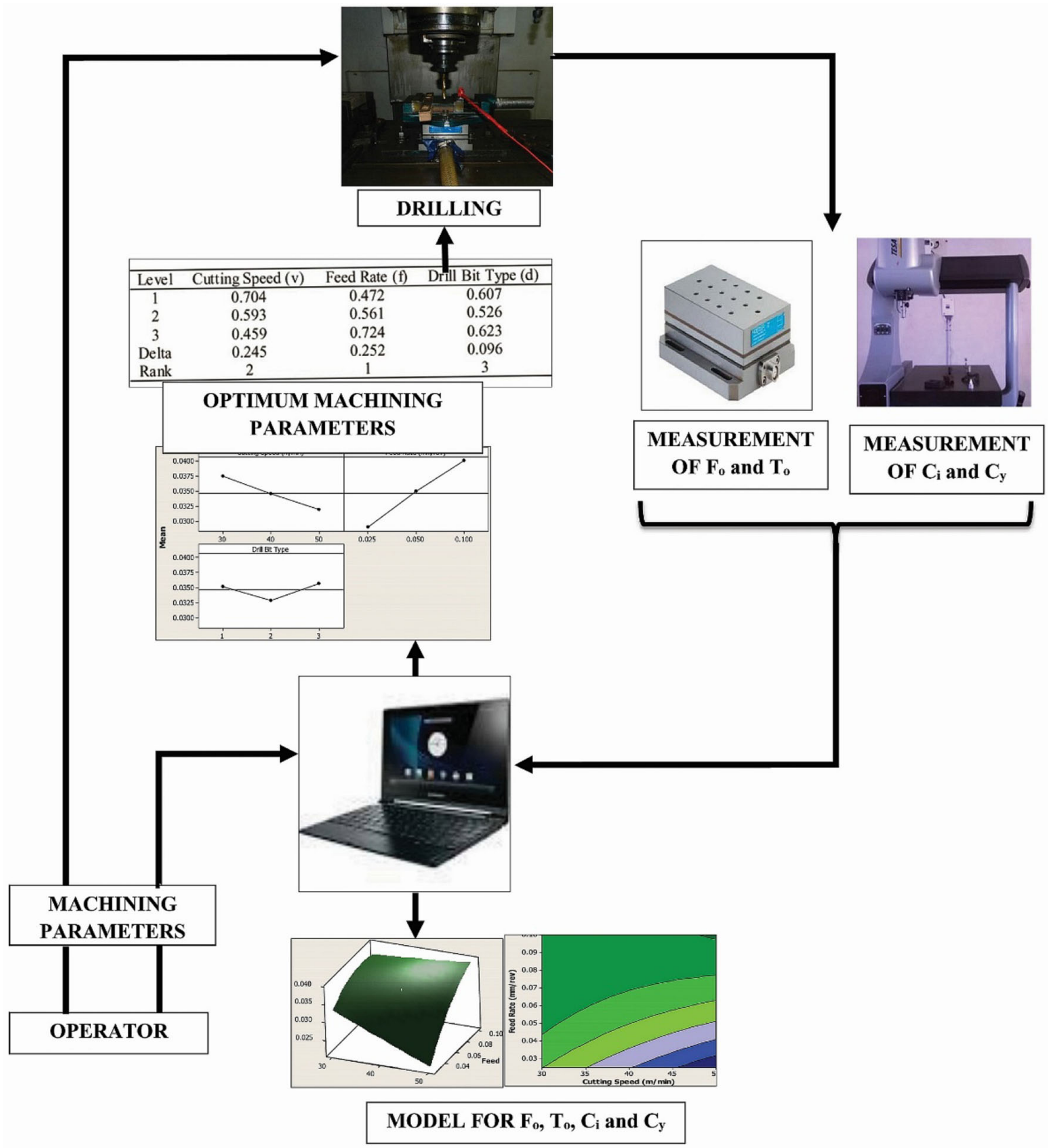

Fig. 1 Schematic diagram of the experimental setup

Table 1 Design parameters and level

Symbol	Drilling parameter	Level		
		1	2	3
v	Cutting speed (m/min)	30	40	50
f	Feed rate (mm/rev)	0.025	0.05	0.1
d	Drill Bit type	HSS	TiAlN	TiN

Kistler multicomponent dynamometer 9257B, was used to measure the three orthogonal components of cutting forces i.e., Fx, Fy and Fz for all the experimental trials. The dynamometer consisted of multi-component measuring system and multi-charge amplifier channels. These channels converted the charge signals from the dynamometer into output signals.

3 Multi-objective Taguchi Techniques

The Taguchi technique can be a methodology for locating the optimum level of the machining process parameters to form the merchandise or process insensitive to the noise factors [19]. The Taguchi technique mainly relies upon the orthogonal matrix of the experimental design. The experimental designs are special orthogonal arrays, which permit the co-occurring impact of several input process parameters to be studied expeditiously. The main aim of this experiment is to associate the orthogonal array design to work out the optimum level for all the issues and to determine the relative significance of the individual factors in terms of their main effects on the responses. The objective functions of Taguchi technique are classified into three classes namely smaller-the-better, larger-the-better and nominal-the-better. The optimum level for an element is that, the level that leads to the best worth of S/N ratio within the experimental design. The methodology to obtain the optimal combination of the drilling process parameter with multi-objective optimization using Taguchi technique is discussed below.

3.1 Membership Function

The first step in multi-objective optimization using Taguchi technique is to compute the normalized value of thrust force, torque, circularity and cylindricity in the range of 0.05–0.95 by using Eq. (1). The values of thrust force, torque, circularity and cylindricity are normalized in the range of 0.05–0.95 to get a comparable sequence because of different scope and dimension of the responses [20]. The above process is to get the best combination of cutting speed, feed rate and drill bit type that simultaneously minimizes the thrust force, torque, circularity and cylindricity. The membership function for the thrust force and torque is given in Eqs. (2 and 3).

$$X_{norm} = \frac{(X - X_{min}) x\ (N_{max} - N_{min})}{(X_{max} - X_{min})} + N_{min} \quad (1)$$

where X_{norm} = normalised value of the variable, N_{min} = 0.05 and N_{max} = 0.95 are the minimum and maximum range of the normalized value, X_{min} and X_{max} are the minimum and maximum value of the input process parameter, respectively.

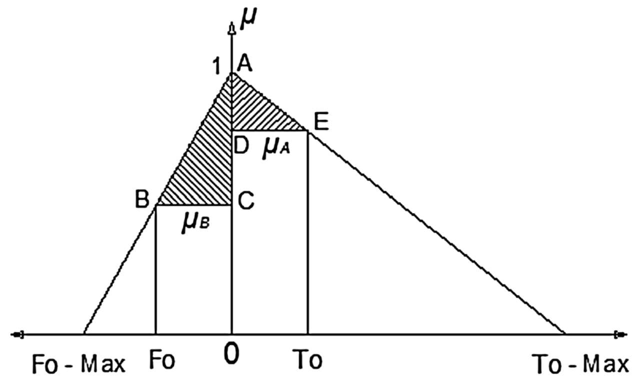

Fig. 2 Membership function for thrust force and torque

The membership function of thrust force and torque are represented in Fig. 2.

$$\mu_A = 1 - \frac{F_o}{F_{o-max}} \quad (2)$$

where μ_A = membership function of thrust force, Fo is the normalized value of the thrust force corresponding to individual experiments, Fo-$_{max}$ is the largest normalized value of the thrust force corresponding to the experimental results.

$$\mu_B = 1 - \frac{T_o}{To-_{max}} \quad (3)$$

where μ_B = membership function of torque, To is the normalized value of the torque corresponding to individual experiments, To-$_{max}$ is the largest normalized value of the thrust torque corresponding to the experimental results. Similarly the membership function of circularity and cylindricity are represented and calculated.

The simultaneous minimization of the thrust force and torque is obtained by calculating the area A, as mentioned in Eq. (4). Similarly, for the circularity and cylindricity also, the area is represented and calculated as

$$A = \frac{1}{2}[F_o(1 - \mu_A) + T_o(1 - \mu_B)] \quad (4)$$

The signal to noise ratio (η) for the combined optimization/area is given in Eq. (5).

$$\eta = -10 \log_{10}(A^2) \quad (5)$$

The experimental design and the normalized value of thrust force, torque, circularity and cylindricity along the area A and signal to noise ratio is shown in Table 2.

Table 2 Normalized value, area and S/N ratio

Exp no	Input process parameters			Normalized value				Area	S/N ratio (db) (η)
	Cutting speed (*v*) (m/min)	Feed rate (*f*) (mm/rev)	Drill bit type (*d*)	Thrust force	Torque	Circularity	Cylindricity		
1	30	0.025	HSS	0.542	0.514	0.590	0.664	0.793	2.016
2	30	0.025	TiAlN	0.458	0.365	0.500	0.541	0.445	7.033
3	30	0.025	TiN	0.466	0.480	0.680	0.705	0.651	3.725
4	30	0.05	HSS	0.695	0.606	0.770	0.786	1.091	− 0.760
5	30	0.05	TiAlN	0.576	0.536	0.680	0.705	0.758	2.401
6	30	0.05	TiN	0.597	0.580	0.860	0.827	1.125	− 1.023
7	30	0.1	HSS	0.950	0.950	0.860	0.745	1.698	− 4.596
8	30	0.1	TiAlN	0.848	0.821	0.770	0.705	1.228	− 1.782
9	30	0.1	TiN	0.882	0.864	0.950	0.827	1.637	− 4.283
10	40	0.025	HSS	0.407	0.239	0.410	0.377	0.332	9.583
11	40	0.025	TiAlN	0.288	0.193	0.500	0.295	0.168	15.506
12	40	0.025	TiN	0.305	0.239	0.590	0.377	0.349	9.151
13	40	0.05	HSS	0.508	0.423	0.680	0.623	0.777	2.190
14	40	0.05	TiAlN	0.398	0.319	0.590	0.500	0.459	6.769
15	40	0.05	TiN	0.712	0.463	0.770	0.582	0.667	3.514
16	40	0.1	HSS	0.763	0.692	0.770	0.909	1.480	− 3.403
17	40	0.1	TiAlN	0.593	0.606	0.590	0.827	1.017	− 0.146
18	40	0.1	TiN	0.687	0.646	0.950	0.950	1.475	− 3.377
19	50	0.025	HSS	0.220	0.205	0.230	0.173	0.089	20.980
20	50	0.025	TiAlN	0.050	0.050	0.050	0.050	0.005	**45.575**
21	50	0.025	TiN	0.125	0.096	0.410	0.214	0.123	18.174
22	50	0.05	HSS	0.339	0.262	0.230	0.582	0.389	8.210
23	50	0.05	TiAlN	0.237	0.147	0.140	0.459	0.159	15.964
24	50	0.05	TiN	0.254	0.228	0.320	0.500	0.285	10.917
25	50	0.1	HSS	0.729	0.566	0.410	0.827	1.132	− 1.081
26	50	0.1	TiAlN	0.492	0.463	0.320	0.745	0.584	4.670
27	50	0.1	TiN	0.515	0.503	0.500	0.909	0.858	1.327

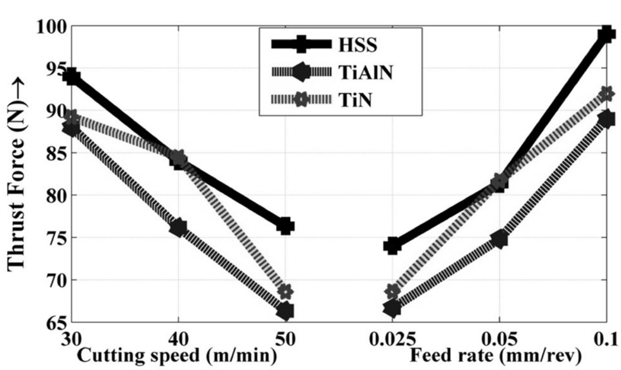

Fig. 3 Main effect plot of Thrust force

4 Results and Discussion

4.1 Effect of Cutting Speed, Feed Rate and Drill Bit Type on Thrust Force

Figure 3 shows the main effect of thrust force in drilling CFRP composite and it clearly indicates that the thrust force decreases gradually with the increase in the cutting speed from 30 to 50 m/min. But in the case of feed rate, the thrust force increases while increasing the feed from 0.025 to 0.1 mm/rev. Thus it's clearly evident that machining at higher cutting speed is critical to scale back the thrust force, because the axial force generated during drilling decreases as the cutting speed increases. Further, it's standard that at maximum cutting speed, temperature increases which causes the material to melt. However the feed rate is concerned, low values are preferred to

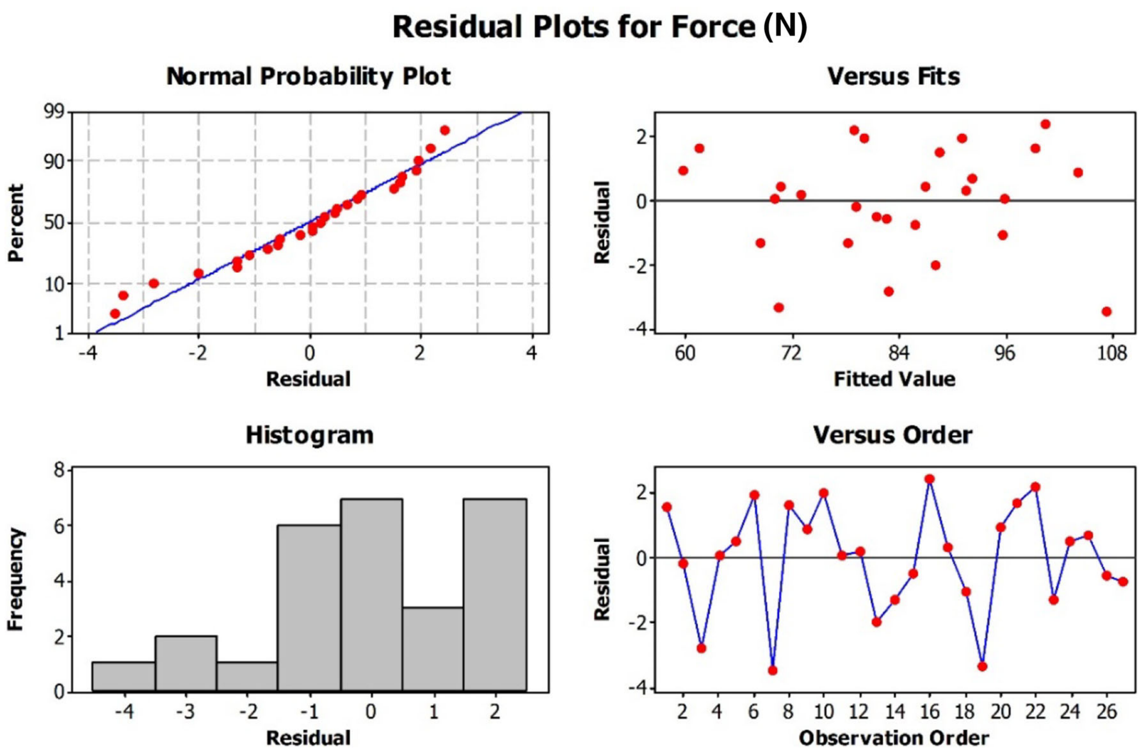

Fig. 4 Residual normal probability plots for Thrust force

minimize the thrust force. Drill bit type of TiAlN produces minimum thrust force when compared with the HSS and TiN.

Figure 4 shows the residual plots for thrust force, which includes normal probability plot, histogram of residuals, residuals of experimental data and residual fitted values. The values of thrust force on this plot form a nearly linear pattern, which indicates that the normal distribution is a good model for this data set. After assessing the coefficients of the regression model, the regression equation (Eqs. (6–8)) for thrust force is as follows:

Table 3 ANOVA for thrust force

Process parameters	DF	SS	V	F	*P* value	C (%)
HSS drill bit						
v	2	392.00	196.00	28.00	0.004	38.13
f	2	608.00	304.00	43.43	0.002	59.15
Error	4	28.00	7.00			2.72
Total	8	1028.00				
TiAlN drill bit						
v	2	562.65	281.32	964.54	0.000	43.15
f	2	740.25	370.12	1268.99	0.000	56.85
Error	4	1.17	0.29			
Total	8	1304.06				
TiN Drill bit						
v	2	572.34	286.17	131.81	0.000	41.95
f	2	783.38	391.69	180.41	0.000	57.42
Error	4	8.68	2.17			0.63
Total	8	1364.40				

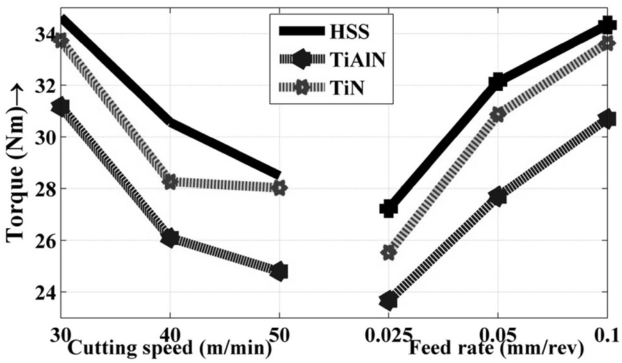

Fig. 5 Main effect plot of Torque

$$Force_{HSS} = 85.3333 + 0.47500v + 177.143f - 0.02v^2 - 1066.67f^2 + 5.57143vf \quad (6)$$

$$Force_{TiAlN} = 98.7444 - 0.847500v + 300.571f - 0.0015v^2 - 71.1111f^2 - 0.0142857vf \quad (7)$$

$$Force_{TiN} = 96.7444 - 0.938333v + 574.190f + 0.0006667v^2 - 1662.22f^2 - 1.57143vf \quad (8)$$

Table 3 shows the results of ANOVA for the thrust force in drilling CFRP laminate. From the Table 3, it is observed that the feed rate contributes 59.15% with HSS, 56.85% with TiAlN and 57.42% with TiN drill bit type followed by the cutting speed, 38.13% with HSS, 43.15% with TiAlN and 41.95% with TiN drill bit type and have statistical significance on the thrust force obtained.

4.2 Effect of Cutting Speed, Feed Rate and Drill Bit Type on Torque

Figure 5 shows the main effect of torque in drilling CFRP composite and it clearly indicates that the torque decreases as the cutting speed increases from 30 to 50 m/min, also as the feed rate increases, the torque increases. This is mainly due to the fact that the excess heat is generated and backed by the low coefficient of thermal conductivity and plastic transition temperature [21]. Drill bit type of TiAlN produces minimum torque when compared with the HSS and TiN.

The residual plots of the torque of normal probability plot, fitted value versus residual plot, histogram of residuals and experiment number versus residual has been shown in Fig. 6. It can be assumed that the residuals of the model for torque are normally distributed. The empirical equation of the torque can be generated as shown below (Eq. (9–11)):

$$Torque_{HSS} = 39.0667 - 0.43500v + 96f + 0.002v^2 + 53.333f^2 - 0.2vf \quad (9)$$

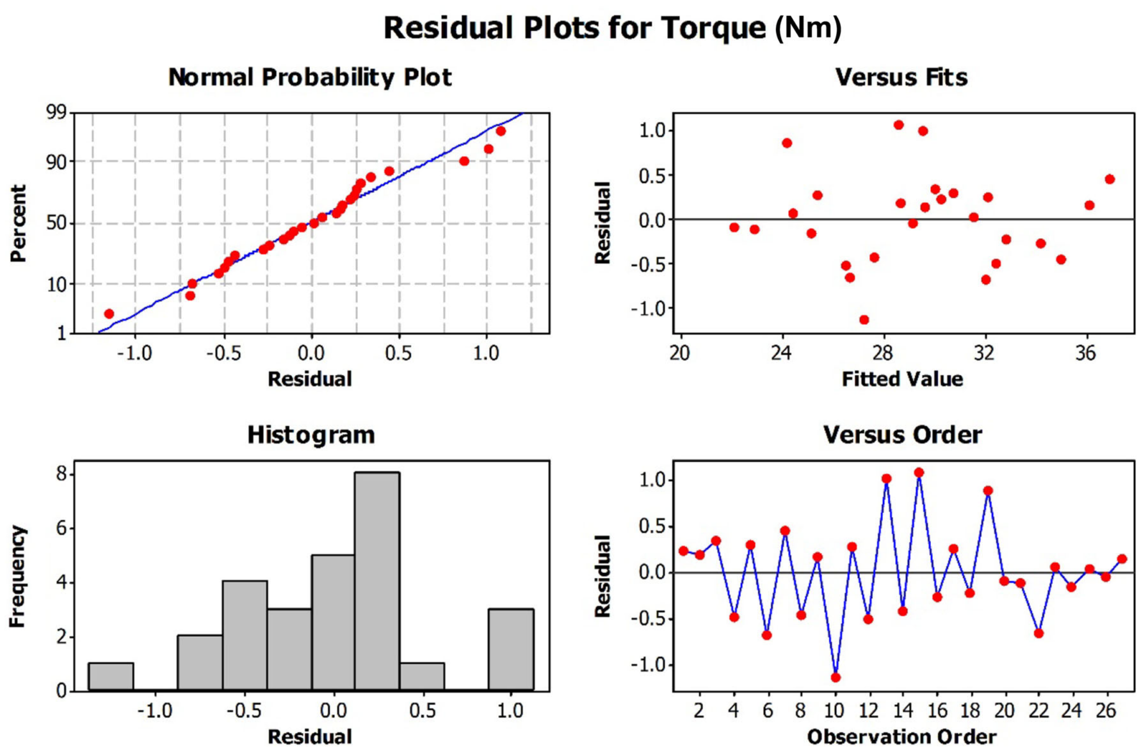

Fig. 6 Residual normal probability plots for torque

Table 4 ANOVA for torque

Process parameters	DF	SS	V	F	P value	P (%)
HSS drill bit						
v	2	49.387	24.693	25.90	0.005	37.43
f	2	78.740	39.370	41.3	0.002	59.68
Error	4	3.813	0.953			2.89
Total	8	131.940				
TiAlN drill bit						
v	2	60.044	30.022	124.49	0.000	47.20
f	2	66.212	33.106	137.28	0.000	52.05
Error	4	0.965	0.241			0.75
Total	8	127.221				
TiN Drill bit						
v	2	70.093	35.046	62.08	0.001	50.74
f	2	65.785	32.893	58.27	0.001	47.63
Error	4	2.258	0.565			1.63
Total	8	138.136				

$$Torque_{TiAlN} = 37.6133 - 0.333417v + 41.5524f - 4.66667e^{-4}v^2 + 63.1111f^2 + 0.932857vf \quad (10)$$

$$Torque_{TiN} = 36.5933 - 0.2495v + 75.8286f - 0.0016v^2 - 106.667f^2 + 0.614286vf \quad (11)$$

Table 4 shows the results of ANOVA for the torque in drilling CFRP laminate. From the Table 4, it is observed that the feed rate contributes 59.68% with HSS, 52.05% with TiAlN and 47.63% with TiN drill bit type followed by the cutting speed, 37.43% with HSS, 47.20% with TiAlN and 50.74% with TiN drill bit type and have statistical significance on the torque obtained.

4.3 Effect of Cutting Speed, Feed Rate and Drill Bit Type on Circularity

Figure 7 shows the main effect plot of circularity in drilling CFRP composite and it clearly indicates that the circularity decreases as the cutting speed increases from 30 to 50 m/min, also as the feed rate increases, the circularity increases. The circularity error increases linearly with the feed rate which in-turn increases vibration and heat. The circularity error is minimum when drilling the CFRP at high cutting speed of 50 m/min, this is mainly due to the achievement of good rotational stability. Also low circularity error at low feed rate is assigned to frictional heating and ploughing effect [1]. Drill bit type of TiAlN produces minimum circularity when compared with the HSS and TiN.

Data normality has been investigated by means of normal probability plot. Residual normal probability plot for circularity is shown in Fig. 8. The goodness of the normal probability plot is seen as all the residuals fall on straight line. The results confirm that errors are positioned normally and scattering is not observed for circularity. The second linear regression equation obtained for circularity is given below (Eqs. (12–14)):

$$Circularity_{HSS} = 0.0152222 - 9.16667e^{-5}v + 0.0180952f - 1.66667e^{-6}v^2 + 0.0888889f^2 + 0.000714286vf \quad (12)$$

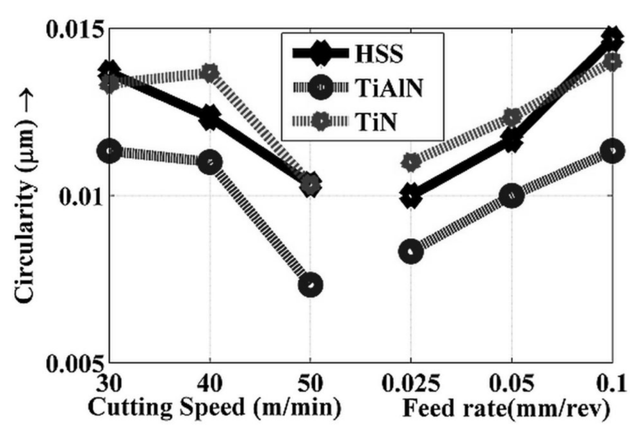

Fig. 7 Main effect plot of Circularity

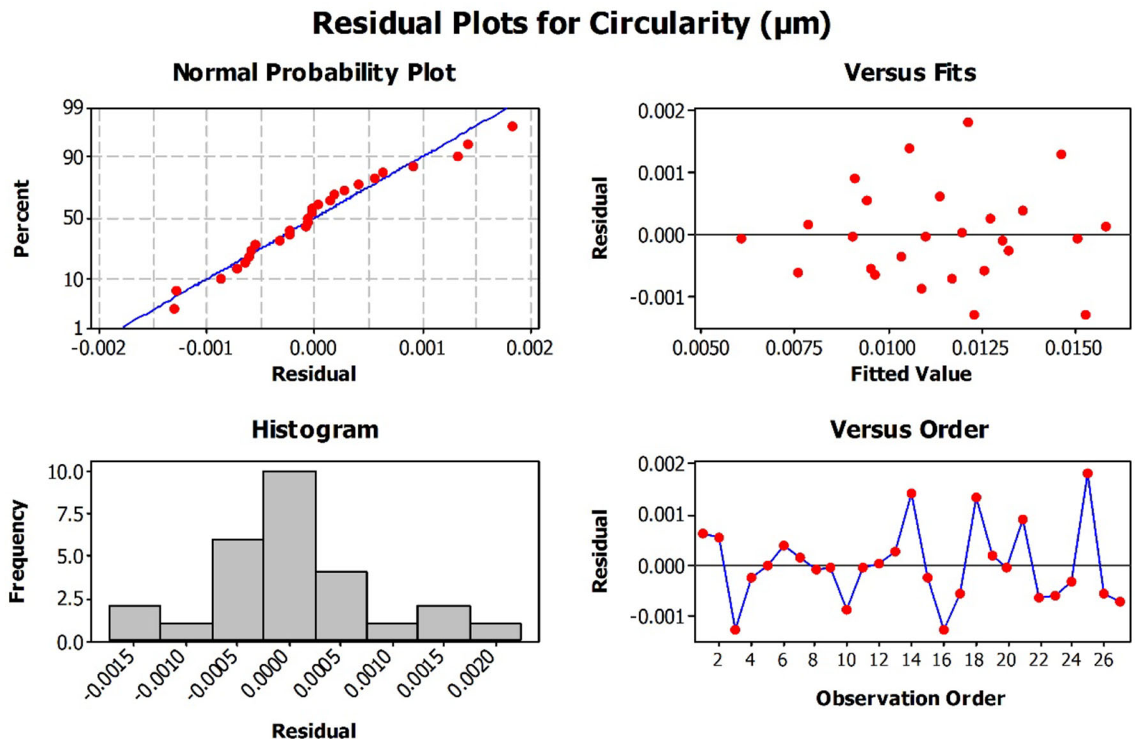

Fig. 8 Residual normal probability plots for circularity

$$Circularity_{TiAlN} = -0.0124444 + 0.0010500v + 0.160f - 1.5e^{-5}v^2 - 0.88889f^2 - 7.31340e^{-19}vf \quad (13)$$

$$Circularity_{TiN} = -0.0145556 + 0.00134167v + 0.110476f - 1.833e^{-5}v^2 - 0.35556f^2 - 4.28571e^{-4}vf \quad (14)$$

Table 5 shows the results of ANOVA for the circularity

Table 5 ANOVA for circularity

Process parameters	DF	SS	V	F	*P* value	*P* (%)
HSS drill bit						
v	2	0.0000202	0.0000101	36.40	0.003	39.69
f	2	0.0000296	0.0000148	53.20	0.001	58.15
Error	4	0.0000011	0.0000003			2.16
Total	8	0.0000509				
TiAlN drill bit						
v	2	0.0000180	0.0000090	27.00	0.005	45.00
f	2	0.0000207	0.0000103	31.00	0.004	51.75
Error	4	0.0000013	0.0000003			3.25
Total	8	0.0000400				
TiN drill bit						
v	2	0.0000202	0.0000101	22.75	0.007	47.87
f	2	0.0000202	0.0000101	22.75	0.007	47.87
Error	4	0.0000018	0.0000004			4.26
Total	8	0.0000422				

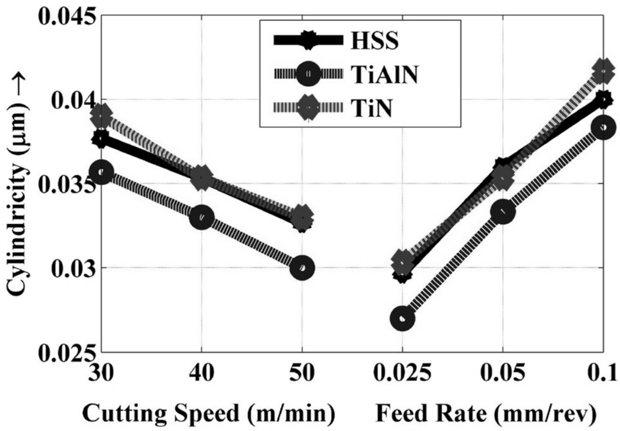

Fig. 9 Main effect plot of cylindricity

in drilling of CFRP laminate. From Table 5, it is observed that both feed rate and cutting speed have a significant effect on circularity with feed rate contributing 58.15% with HSS, 51.75% with TiAlN and 47.87% with TiN drill bit type and cutting speed, 39.69% with HSS, 45.00% with TiAlN and 47.87% with TiN drill bit type. Low feed rate (0.025 mm/rev), high cutting speed (50 m/min) and TiAlN drill bit type are the best operating condition for achieving the best circularity value.

4.4 Effect of Cutting Speed, Feed Rate and Drill Bit Type on Cylindricity

Figure 9 shows the main effect plot of cylindricity in drilling CFRP composite and it clearly indicates that the cylindricity decreases gradually as the cutting speed increases from 30 to 50 m/min, also as the feed rate increases from 0.025 to 0.1 mm/rev, the cylindricity increases rapidly. Drill bit type of TiAlN produces minimum cylindricity when compared with the HSS and TiN. As seen in Fig. 9, the controlled factors at the levels of *v3* (a 50 m/min cutting speed), *f1* (a 0.025 mm/rev feed rate) and TiAlN drill bit give optimum performance characteristics when the cylindricity analysis is used.

Figure 10 shows the residual plots for cylindricity, which includes normal probability plot, histogram of residuals, residuals of experimental data and residual fitted values. The values of cylindricity on the resulting plot is approximately linear, hence it is assumed that the error terms are normally distributed. The histogram of residuals suggests that the residuals (and hence the error terms) are normally distributed. After assessing the coefficients of the regression model, the regression equation for cylindricity is as follows (Eqs. (15–17)):

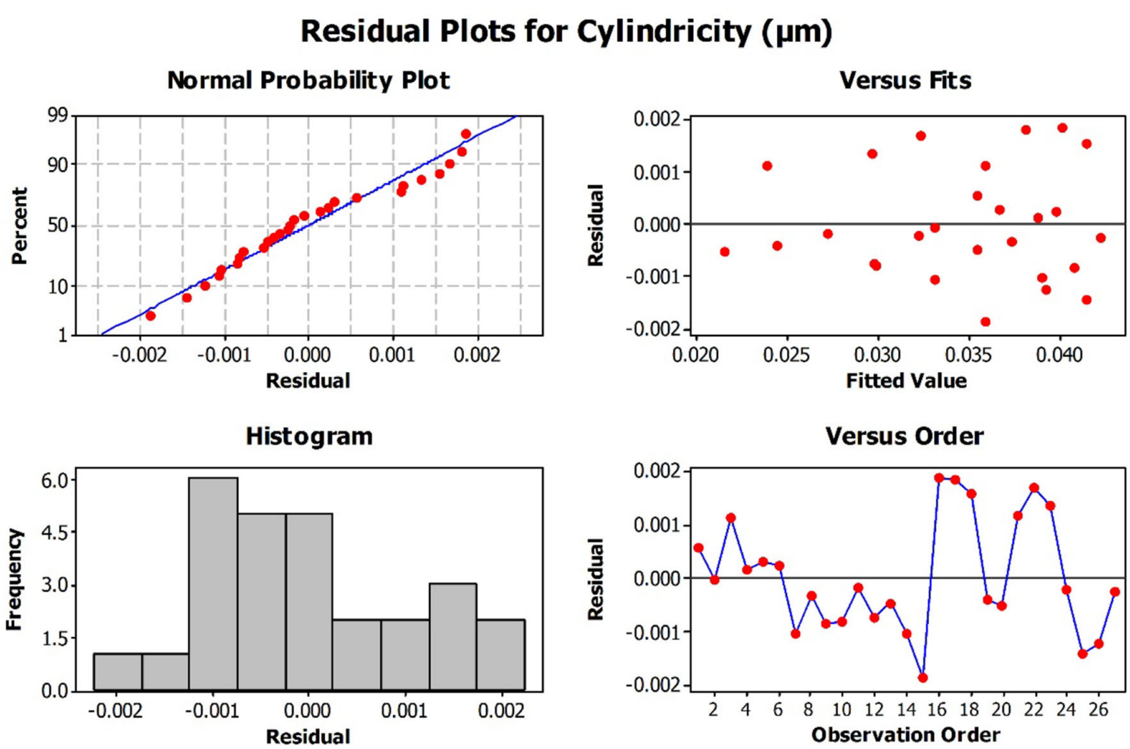

Fig. 10 Residual normal probability plots for cylindricity

Table 6 ANOVA for cylindricity

Process Parameters	DF	SS	V	F	*P* value	P (%)
HSS drill bit						
v	2	0.0000282	0.0000141	8.76	0.035	10.68
f	2	0.0002296	0.0001148	71.24	0.001	86.90
Error	4	0.0000064	0.0000016			2.42
Total	8	0.0002642				
TiAlN drill bit						
v	2	0.0000376	0.0000188	10.56	0.025	14.41
f	2	0.0002162	0.0001081	60.81	0.001	82.87
Error	4	0.0000071	0.0000018			2.72
Total	8	0.0002609				
TiN drill bit						
v	2	0.0000816	0.0000408	13.11	0.018	24.31
f	2	0.0002416	0.0001208	38.82	0.002	72.00
Error	4	0.0000124	0.0000031			3.69
Total	8	0.0003356				

$$Cylindricity_{HSS} = 0.0366667 - 5.08333e^{-4}v + 0.344762f + 1.66667e^{-6}v^2 - 2.31111f^2 + 0.00271429vf \tag{15}$$

$$Cylindricity_{TiAlN} = 0.0358889 - 5.08333e^{-4}v + 0.307619f + 1.66667e^{-6}v^2 - 1.86667f^2 + 0.00214286vf \tag{16}$$

$$Cylindricity_{TiN} = 0.0567778 - 0.00113333v + 0.153333f + 6.66667e^{-6}v^2 - 1.15556f^2 + 0.0040vf \tag{17}$$

Table 6 shows the results of ANOVA for the cylindricity in drilling CFRP laminate. From the Table 6, it is observed that the most significant process parameter affecting the cylindricity is feed rate with a percentage contribution of 86.90% with HSS, 82.87% with TiAlN and 72.00% with TiN drill bit type followed by the cutting speed, 10.68% with HSS, 14.41% with TiAlN and 24.31% with TiN drill bit type.

Figure 11 shows the S/N ratio of the response variable while drilling CFRP composite for multi-performance characteristics. It's clear from the graph that minimum thrust force, torque, circularity and cylindricity can be achieved by drilling with cutting speed (50 m/min), feed rate (0.025 mm/rev) and TiAlN drill bit.

The ANOVA results of the drilling CFRP with multi-performance characteristics are presented in Table 7. The results indicate that the feed rate is the most significant process parameter which affects the responses. Also it is observed from the ANOVA results that the contribution of error is high in all the three drill bit type, which is mainly due to the interaction effect of cutting speed and feed rate.

5 Confirmation/Validation

5.1 Confirmation Test for Taguchi Technique

The predicted value for the confirmation test is calculated from the Eq. (18).

$$\eta_0 = \eta_{om} + \sum_{i=1}^{k} (\bar{\eta}_{oi} - \eta_{om}) \tag{18}$$

The confirmation test has been carried out at the optimal level to correlate the experimental and predicted values. The results of the test are presented in Table 8. The

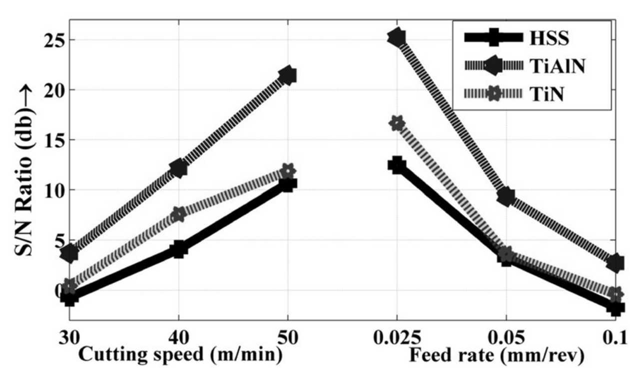

Fig. 11 Mean S/N ratio of the response

Table 7 ANOVA results of S/N ratio

Process parameters	DF	SS	V	F	P (%)
HSS drill bit					
v	2	168.42	84.21	5.43	32.34
f	2	290.23	145.12	9.36	55.74
Error	4	62.03	15.51		11.92
Total	8	520.69			
TiAlN drill bit					
v	2	425.17	212.59	12.03	42.33
f	2	508.62	254.31	14.39	50.63
Error	4	70.71	17.68		7.04
Total	8	1004.50			
TiN drill bit					
v	2	176.51	88.25	16.95	41.00
f	2	233.16	116.58	22.39	54.16
Error	4	20.83	5.21		4.84
Total	8	430.49			

Table 8 Confirmation test for Taguchi technique

	Optimal Input Process Parameters	
	Predicted Values	Experimental Values
Level	$v_3f_1d_2$	$v_3f_1d_2$
S/N Ratio	20.345	45.575

improvement in the S/N ratio of the predicted value clearly indicates that the proposed method can be effectively used for drilling CFRP.

5.2 Confirmation Test for RSM

The validation of the RSM has been successfully done by comparing the actual experimental values and the predicted values of the linear regression model. Table 9 shows the actual experimental values and predicted values of the thrust force, torque, circularity and cylindricity. From the Table 9, it is observed that the errors lies from − 9.72 to 9.38%. The validity of the model is said to be satisfactory as the errors are within the acceptable limit [22].

6 Conclusions

In this paper, optimization of drilling process parameters with multi-performance characteristics (thrust force and torque) in dry drilling of CFRP was determined by using Taguchi technique. From the response table of the mean S/N ratio, the largest value of S/N ratio for the drilling parameters was selected as the optimum level, for the multi-performance characteristics. Empirical equations were developed for all the four responses using the significant input parameters and their interactions. The conclusions drawn from the study have been summarized as follows:

1. The optimum process parameter setting for minimizing the thrust force, torque, circularity and cylindricity in drilling CFRP is cutting speed 50 m/min, feed rate 0.025 mm/rev and drill bit type of TiAlN.
2. From the confirmation test it is evident that the multi-objective Taguchi technique is more suitable for minimizing the thrust force, torque, circularity and cylindricity in drilling of CFRP. Also as the error deviation between actual and predicted values of RSM is reasonable and hence validation of regression model is satisfactory.
3. Feed rate is the most significant factor which affects the thrust force, torque, circularity and cylindricity in drilling of CFRP.

Table 9 Confirmation of the tests and validity of the RSM model

Test No	Cutting speed (m/min)	Feed rate (mm/rev)	Drill bit type	Predicted force values	Experimental force values	Error (%)
1	55	0.075	TiAlN	69.6783	73.5	5.20
2	45	0.1	TiN	89.5948	92.6	3.25
3	48	0.09	TiAlN	81.0221	86.4	6.22
Test No	Cutting speed (m/min)	Feed rate (mm/rev)	Drill bit type	Predicted torque values	Experimental torque values	Error (%)
1	55	0.075	TiAlN	25.18316	26.81	6.03
2	45	0.1	TiN	31.40	28.7	− 9.43
3	48	0.09	TiAlN	28.81	27.8	− 3.65
Test no	Cutting speed (m/min)	Feed rate (mm/rev)	Drill bit type	Predicted circularity values	Experimental circularity values	Error (%)
1	55	0.075	TiAlN	0.006931	0.007	1.00
2	45	0.1	TiN	0.014265	0.013	− 9.72
3	48	0.09	TiAlN	0.020596	0.01	− 5.95
Test No	Cutting speed (m/min)	Feed rate (mm/rev)	Drill bit type	Predicted cylindricity values	Experimental cylindricity values	Error (%)
1	55	0.075	TiAlN	0.034383	0.036	4.50
2	45	0.1	TiN	0.038127	0.04	4.68
3	48	0.09	TiAlN	0.037152	0.041	9.39

4. Thus to increase the production capacity with minimum machining time, a proper combination of cutting speed (maximum value) and feed rate (minimum value) are chosen to reduce the thrust force, torque, circularity and cylindricity.

References

1. Prasanna J, Karunamoorthy L, Raman M V, Prashanth S, and Chordia D R, *Meas* **48** (2014) 346.
2. Shanmughasundaram P, and Subramanian R, *J Mater Res Technol* **3** (2014) 150.
3. Chatterjee S, Abhishek K, Mahapatra S S, Datta S, and Yadav RK, *Proc Eng* **97** (2014) 78.
4. Pandey R K, and Panda S S, *Meas* **47** (2014) 386.
5. Pandey R K, and Panda S S, *J Orthoped* **12** (2015) 39.
6. Pinho L V, Carou D, and Davim J P, *Indian J Eng Mater Sci* **23** (2016) 134.
7. Nasir A A, Azmi A I, and Khalil A N, *Meas* **75** (2015) 298.
8. Siddiquee A N, Khan Z A, Goel P, Kumar M, Agarwal G, and Khan N Z, *Proc Mater Sci* **6** (2014) 1217.
9. Rao S R, and Padmanabhan G, *J Sci Ind Res* **73** (2014) 251.
10. Kannan T D, Kumar B S, and Baskar N, *Proc Mater Sci* **5** (2014) 2242.
11. Abhishek K, Datta S, and Mahapatra S S, *Meas* **77** (2015) 222.
12. Parthiban A, Ravikumar R, Zubar H A, and Duraiselvam M, *J Sci Ind Res* **73** (2014) 387.
13. Prakash S, Mercy J L, Salugu M K, and Vineeth K S M, *Mater Today: Proc* **2** (2015) 1541.
14. Yang Y S, and Huang W, *Expert Syst Appl* **39** (2012) 743.
15. Khan Z A, Siddiquee A N, Khan N Z, Khan U, and Quadir G A, *Proc Mater Sci* **6** (2014) 1683.
16. Sahoo A K, and Pradhan S, *Meas*, **46** (2013) 3064.
17. Gowda B U, Ravindra H V, Ullas M, Prakash G N, and Ugrasen G, *Proc Mater Sci* **6** (2014) 1780.
18. Pandey R K, and Panda S S, *Meas* **59** (2015) 9.
19. Taguchi G, *Introduction to quality engineering: designing quality into products and processes* (1986).
20. Assarzadeh S, and Ghoreishi M, *Int J Adv Manuf Tech*, **39** (2008) 488.
21. Vijayalakshmi Rao R, Manujesh B J, Umashankar K S, and Sham Aan M P, *Trans Indian Inst Met* **65** (2012) 71.
22. Kannan T, and Murugan N, *Weld J*, **85** (2006), 91.