Application of Taguchi approach to seek optimum drilling parameters for woven fabric carbon fibre/epoxy laminates

Sai Somanadha Sastry Konduri, Department of Mechanical Engineering, Koneru Lakshmaiah University, Vaddeswaram, Andhra Pradesh, India, sksom246@gmail.com
V D S R Manideep Kumar Kalavala, Department of Mechanical Engineering, Koneru Lakshmaiah University, Vaddeswaram, Andhra Pradesh, India, k.mani7176@gmail.com
Priyanka Mandala, Department of Mechanical Engineering, Koneru Lakshmaiah University, Vaddeswaram, Andhra Pradesh, India, mandala.priyanka1995@gmail.com
Raghu Ram Manapragada, Department of Mechanical Engineering, Koneru Lakshmaiah University, Vaddeswaram, Andhra Pradesh, India, m.raghuram2699@gmail.com
B. Nageswara Rao, Department of Mechanical Engineering, Koneru Lakshmaiah University, Vaddeswaram, Andhra Pradesh, India, bnrao52@rediffmail.com

***Abstract*-This paper presents optimum drilling parameters for woven fabric carbon fiber/epoxy laminates following the Taguchi design of experiment. Analysis of variance (ANOVA) is performed to trace the statistically significance of input parameter viz. feed rate and cutting speed. A simple multi-objective optimization approach is adopted for identifying a set of optimum drilling parameters to minimize the thrust force, drilling torque and delamination factor. An efficient prediction methodology is considered to estimate the output responses for the identified optimum drilling parameters and validated through comparison of test results.**

***Keywords:* ANOVA, Delamination factor, Drilling torque, Taguchi approach, Thrust force, Woven fabric carbon fibre/epoxy laminate.**

I. INTRODUCTION

With the advent of composite materials and their extensive use in aerospace and defence, drilling of holes into the laminates is unavoidable to facilitate bolting or riveting to the main load-bearing structures [1, 2]. In fact drilling of composite laminates generates damages in the form of delamination at macro level and at micro level in the form of cracks, fiber-matrix debonding, etc. Damage created during the drilling of a laminate (see Fig. 1) is classified as peel-up delamination (which depends on the feed rate and on the helix angle of the twist drift) at the twist drill entrance and push-down delamination (which is mainly affected by the feed rate) at the twist drill exit [3-5]. Currently, there is a demand for woven composites in aerospace and industrial applications [6-11]. Khashaba et al. [7] have performed drilling analysis on glass fiber reinforced/epoxy composites. Koboevic et al. [8] have performed drilling operations on woven fabric carbon fiber/epoxy laminates using three different types of 6 mm diameter drills (see Fig. 2). They have measured thrust force (F_0) and drilling torque (M) utilizing a Kistler® piezoelectric dynamometer 9271A with load amplifier. A microscope (OLYMPUS S7X9 with 30× magnification and $1\mu m$ resolution) is used to measure the damage due to drilling of the hole, whereas digital camera is used for photos at entrance and exit side of the hole. Software is used to measure the delamination area for evaluating the delamination factor, K_d (See Fig. 3).

Feed rate, cutting speed and the tool geometry (i.e., the type of drill) are the prime input parameters, whereas the thrust force (F_0), drilling torque (M) and delamination factor, K_d are the measured/ evaluated output responses.

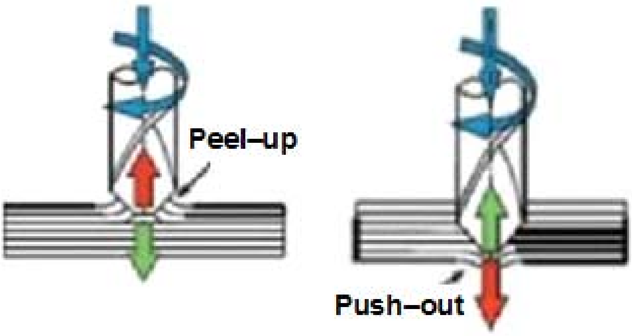

Figure 1. Peel-up and push-out delamination

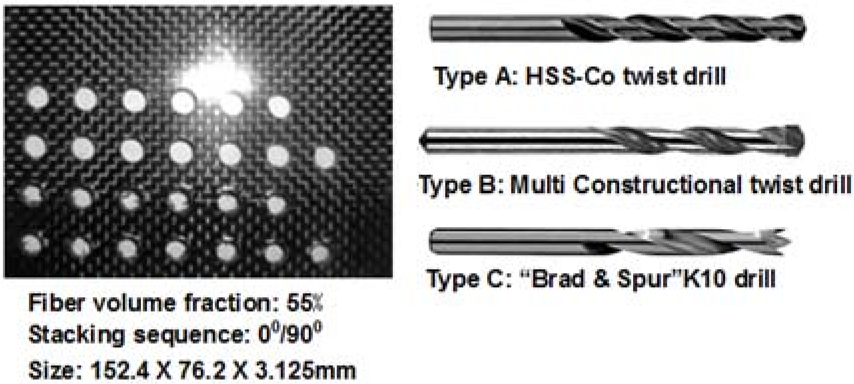

Figure 2. Types of drills used in drilling operation on a laminate

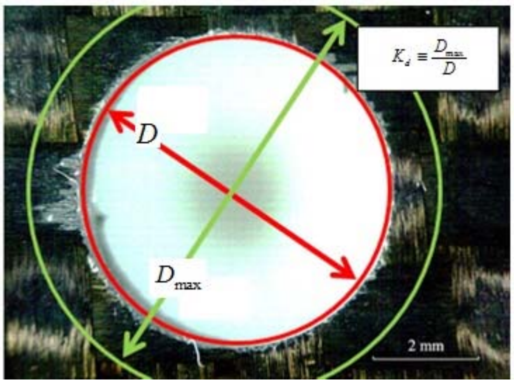

Figure 3. Evaluation of delamination factor (K_d) in a laminate having drilled hole

They have specified three levels of cutting speed as 10, 14 and 18 mm/min, whereas that of feed rate are 0.02, 0.05 and 0.08 mm/rev**.** Figures 4 to 6 show the variation of output responses at each test run under the same cutting speed and feed rate for the three types of drills. It is observed that type C drill (: Brad & Spur drill) shows better performance (i.e., lower output response is better) than type A drill (: HSS-Co twist drill) and type B drill (: Multi Constructional twist drill).

Koboevic et al. [8] have processed the test data by the “Design Expert” software package and generated mathematical models for the output responses in terms of input variables. There is no guarantee that the set of input parameters identified will be same for all the optimum output responses. In such situations, a simple and reliable multi-objective optimization approach is more appropriate [12-14]. This paper considers an efficient prediction methodology [15] to estimate the output responses for the identified optimum drilling parameters. It is noted from Figures 4 to 6 that the desired responses (i.e., lower output responses is better) can be achieved in drilling of holes for woven fiber carbon/epoxy composites through type C drill and hence the corresponding test data will be analyzed in the present study following the Taguchi design of experiment and performing the analysis of variance (ANOVA) to trace the statistically significance of input parameter viz. feed rate and cutting speed. The estimates of the output responses are improved by introducing suitably the fictitious input parameters as in [15] without changing the test runs and demonstrated that the test results are within the expected range of the output responses.

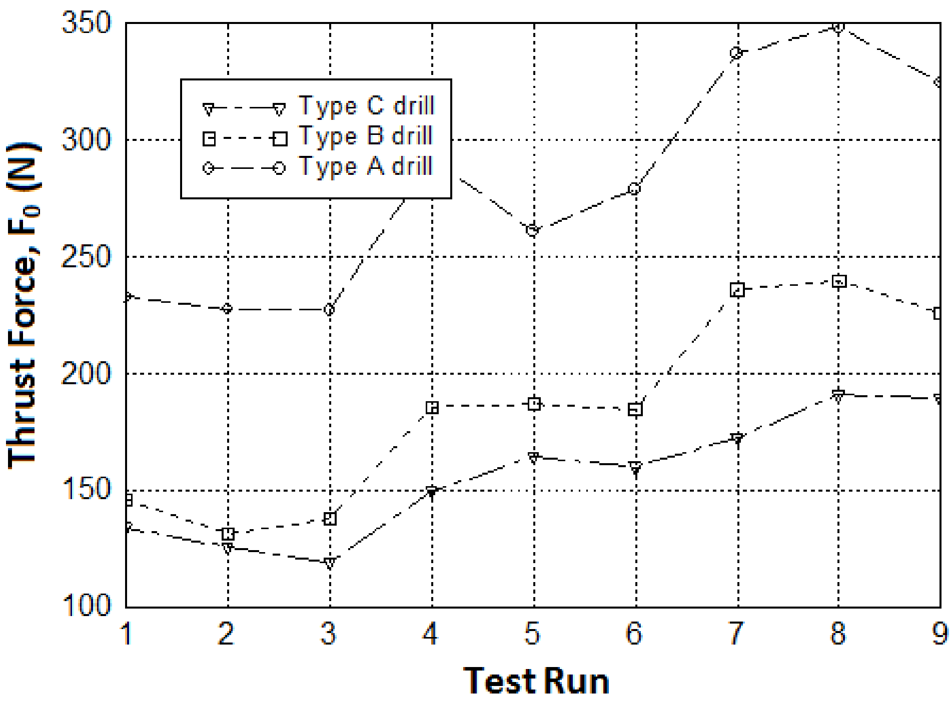

Figure 4. Comparison of thrust force for different types of drills under the same cutting conditions

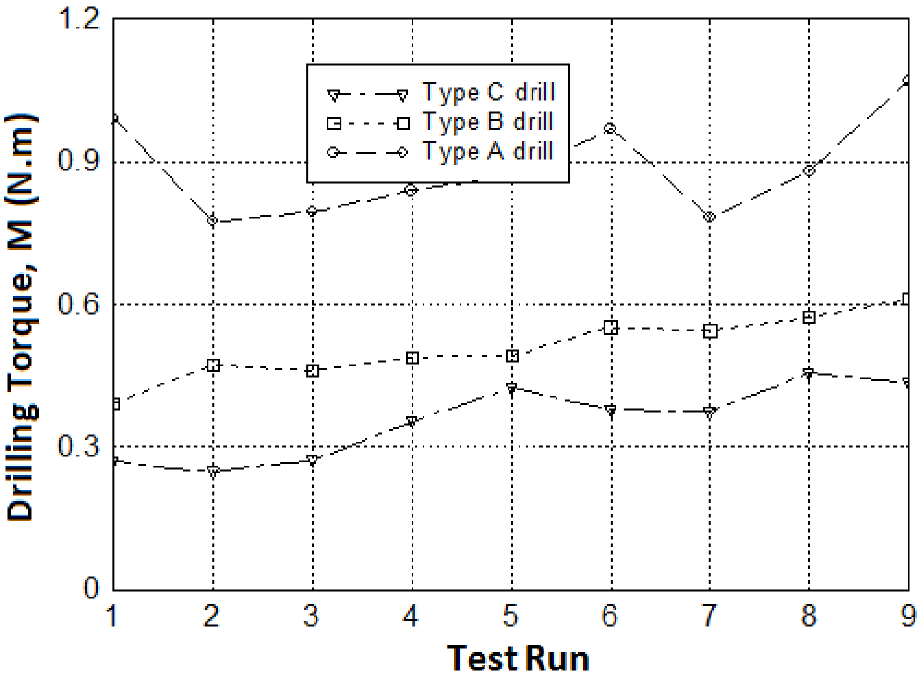

Figure 5. Comparison of drilling torque for different types of drills under the same cutting conditions

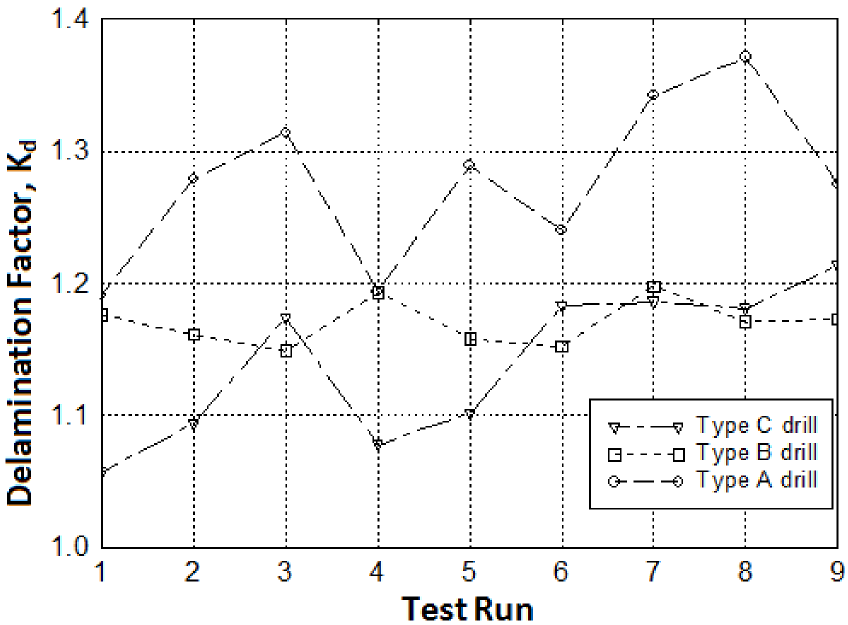

Figure 6. Comparison of delamination factor for different types of drills under the same cutting conditions

II. TAGUCHI'S DESIGN OF EXPERIMENTS AND ANALYSIS OF VARIANCE

The assignment levels of process parameters (viz., feed rate and cutting speed) and the output responses (viz., thrust force, drilling torque and delamination factor) for the assigned process parameters as per L_9 orthogonal array are presented in Table I. As per the Taguchi design of experiments, the relation between the number of experiments ($N_{Taguchi}$) and the factors or input parameters with their assigned levels is [1]

$$N_{Taguchi} = 1 + Number\ of\ \ factors \times (Number\ of\ Levels - 1) \quad (1)$$

Equation (1) gives 4 number of factors, when $N_{Taguchi}$=9 and *Number of Levels*=3. In [8], only two factors are considered and hence two fictitious factors F1 and F2 are introduced in Table I. The output response in each test run is a combination of different process parameter levels. Mean value of the output response is evaluated from the level setting of each process parameter, whose sensitivity on the output response is assessed by computing the sum of the squares of deviation of each of mean value from grand mean value. Analysis of variance (ANOVA) is performed as in Ref. [12] to trace the optimum process parameters for obtaining optimum output responses. It is noted from the ANOVA results of Table II that feed rate has immense effect on the output responses (i.e., high % contribution).

Estimation of the output response ($\hat{\eta}$) can be made from (2) for each test run by considering η_i as the mean value of η at the level of the process parameter (i) [12-15]

$$\hat{\eta} = \eta_m + \sum_{i=1}^{p} (\eta_i - \eta_m) \quad (2)$$

Here η_m is the overall mean of η with 9 test runs; and *p* is the number of process parameters. Tables III to V gi ve comparison on the estimates of output responses.

TABLE I. Performance output responses (viz., thrust force, drilling torque and delamination factor) for the assigned process parameters as per L_9 orthogonal array.

Assignment levels of process parameters

Control Factors (Input parameters)	Designated Factor	Level -1	Level-2	Level-3
Feed rate (mm/rev)	A	0.02	0.05	0.08
Cutting speed (mm/min)	C	10	14	18
Fictitious	F1	f_1	f_2	f_3
Fictitious	F2	f_4	f_5	f_6

Output responses

Test Run	Levels of input parameters				Thrust force, F_0 (N)	Drilling torque, M (N.m)	Delamination factor, K_d	ψ Eq.(3)
	A	C	F1	F2				
1	1	1	1	1	134.013	0.269	1.057	0.6905
2	1	2	2	2	125.820	0.249	1.094	0.6724
3	1	3	3	3	118.833	0.273	1.174	0.7587
4	2	1	2	3	149.740	0.354	1.078	0.7822
5	2	2	3	1	164.438	0.426	1.102	0.8638
6	2	3	1	2	159.922	0.378	1.183	0.8436
7	3	1	3	2	172.440	0.374	1.186	0.8624
8	3	2	1	3	191.016	0.456	1.181	0.9499
9	3	3	2	1	189.103	0.436	1.214	0.9414

TABLE II. Analysis of variance (ANOVA) on the output responses of TABLE I

Parameters	1-Mean	2-Mean	3-Mean	Sum of squares	% contribution
Thrust force, F_0 (N)					
A	126.222	158.033	184.186	5055.7	91.9
C	152.064	160.424	155.952	105.0	1.9
F1	161.650	154.887	151.903	149.7	2.6
F2	162.488	152.727	153.196	181.8	3.6
Drilling torque, M (N.m)					
A	0.263	0.386	0.422	0.0417	86.2
C	0.332	0.377	0.362	0.0031	6.4
F1	0.367	0.346	0.357	0.0007	1.5
F2	0.377	0.333	0.361	0.0029	5.8
Delamination factor, K_d					
A	1.108	1.121	1.193	0.0126	56.3
C	1.107	1.125	1.190	0.0074	33.0
F1	1.140	1.128	1.154	0.0010	4.5
F2	1.124	1.154	1.144	0.0014	6.2

TABLE III. Comparison on the estimates of thrust force, F_0 (N)

Test run	Test [8]	Estimates [8]	Present study		
			Only process parameters	Inclusion of fictitious parameters	Expected range
1	134.013	129.78	122.14	133.98	114.48 – 133.98
2	125.820	131.13	130.50	125.82	122.84 – 142.34
3	118.833	117.75	126.03	118.83	118.36 – 137.87
4	149.740	154.58	153.95	149.74	146.29 – 165.79
5	164.438	163.89	162.31	164.41	154.65 – 174.15
6	159.922	158.47	157.84	159.92	150.17 – 169.68
7	172.440	171.83	180.10	172.44	172.44 – 191.95
8	191.016	189.10	188.46	191.02	180.80 – 200.31
9	189.103	191.64	184.00	189.07	176.33 – 195.84

TABLE IV. Comparison on the estimates of drilling torque, M (N.m)

Test run	Test [8]	Estimates [8]	Present study		
			Only process parameters	Inclusion of fictitious parameters	Expected range
1	0.269	0.269	0.238	0.268	0.203 – 0.268
2	0.249	0.296	0.283	0.248	0.248 – 0.313
3	0.273	0.272	0.268	0.272	0.233 – 0.298
4	0.354	0.355	0.361	0.354	0.326 – 0.391
5	0.426	0.417	0.406	0.426	0.371 – 0.436
6	0.378	0.382	0.391	0.377	0.356 – 0.421
7	0.374	0.374	0.397	0.373	0.362 – 0.427
8	0.456	0.459	0.442	0.456	0.407 – 0.472
9	0.436	0.433	0.427	0.436	0.392– 0.457

TABLE V. Comparison on the estimates of delamination factor, K_d

Test run	Test [8]	Estimates [8]	Present study		
			Only process parameters	Inclusion of fictitious parameters	Expected range
1	1.057	1.052	1.0744	1.0575	1.0452 – 1.1012
2	1.094	1.090	1.0924	1.0932	1.0632 – 1.1192
3	1.174	1.178	1.1577	1.1745	1.1285 – 1.1845
4	1.078	1.085	1.0874	1.0782	1.0582 – 1.1142
5	1.102	1.101	1.1054	1.1022	1.0762 – 1.1322
6	1.183	1.166	1.1707	1.1838	1.1415 – 1.1975
7	1.186	1.182	1.1594	1.1862	1.1302 – 1.1862
8	1.181	1.175	1.1774	1.1805	1.1482 – 1.2042
9	1.214	1.219	1.2427	1.2135	1.2135 – 1.2695

The expected range of output response is arrived considering the fictitious parameters and the levels of lowest and highest mean values of the output response (η). It is very interesting to note from Tables III to V that the estimates of output responses from the mathematical models [8] and those from (2) with only process parameters are reasonably in good agreement with test results [8]. Inclusion of fictitious parameters in (2), the estimates of output responses are closely matching well with test results [8]. It is noted from [8] that test run-5 is repeated four times and presented the measured thrust force values as 163.045, 163.469, 163.865 and 168.011N respectively. These values are within the expected range in test run-5 of Table III. The measured drilling torque presented in [8] by repeating test run-5 four times are 0.415, 0.419, 0.411 and 0.420 N.m respectively, which are in the expected range in Table IV. The evaluated delamination factor in [8] by repeating test run-5 four times are 1.098, 1.086,1.112 and 1.108 repectively, which are within the expected range in Table V. Comparison of output responses for the test runs in Tables III to V demonstrates the potential of using (2) with inclusion of fictitious input parameters without performing additional tests.

There is a need to specify a set of optimal process parameters to achieve minimum thrust force (F_0), drilling torque (M) and minimum delamination factor (K_d). For this purpose, a non-dimensional parameter ψ is introduced as

$$\psi = \omega_1\left(\frac{F_0}{F_{0\max}}\right) + \omega_2\left(\frac{M}{M_{\max}}\right) + \omega_3\left(\frac{K_d}{K_{d\max}}\right) \quad (3)$$

Here ω_1, ω_2 and ω_3 are weighing factors, whose sum is unity. To have common optimum process conditions, equal weight are given (i.e., $\omega_1 = \omega_2 = \omega_3 = 1/3$). Considering η_i as the mean value of η at the optimal for the process parameter (i) in (2), the maximum values estimated for the output responses are: $F_{0\max}$ =200.31N; $M_{\max}$ =0.472N.m; and $K_{d\max}$ = 1.2695 . The ψ values for all 9 test runs of Table I are generated and ANOVA is performed on ψ and obtained optimum process parameters to achieve minimum ψ . The selected process parameters are 0.02 mm/rev feed rate and 10 mm/min cutting speed.

The lowest first mean value of the output responses (viz., thirst force, drilling torque and delamination factor) for parameters A and C in Table II indicates the confirmation of the identified process parameters. This corresponds to the case of Test run-1 in Tables III to V. The expected range of the output responses for the test run-1 is found to be within the range of the other test runs. For the selected process parameters of 0.02 mm/rev feed rate and 10 mm/min cutting speed , the expected range of output responses are: thrust force =114.48 – 133.98N; drilling torque =0.203 – 0.268N.m; and delamination factor = 1.0452 – 1.1012. The test data corresponding to this case are 134.013N, 0.269N.m, and 1.059 respectively, which are close to the expected range.

III. CONCLUDING REMARKS

There is a demand for woven composites in aerospace and industrial applications. Drilling of holes into the laminates is unavoidable to facilitate bolting or riveting to the main load-bearing structures. Following the Taguchi design of experiments, optimum drilling parameters are arrived for woven fabric carbon fiber/epoxy laminates. The significance of feed rate and cutting speed is examined by performing analysis of variance (ANOVA). For identifying a set of optimum drilling parameters to minimize the thrust force, drilling torque and delamination factor, a simple multi-objective optimization approach is considered. An efficient prediction methodology is adopted to estimate the range of output responses for the identified optimum drilling parameters.

ACKNOWLEDGMENT

The authors would like to thank the reviewers for their valuable comments/suggestions to improve the clarity of presentation.

REFERENCES

[1] B. Srinivasa Rao, P. Rudramoorthy, S. Srinivas and B. Nageswara Rao, “Effect of drilling induced damage on notched tensile strength and pin-bearing strength of woven GFR-epoxy composites”, *Materials Science & Engineering A*, vol.472, pp.347-352, 2008.

[2] T. Parameshwaran Pillai, P.R. Lakshminarayanan and B. Nageswara Rao, “Taguchi’s approach to examine the effect of drilling induced damage on the notched tensile strength of woven GFR-epoxy composite”, *Advanced Composite Materials*, vol.20, pp.261-275, 2011.

[3] H. Hocheng and C.C. Tsao, “Comprehensive analysis of delamination in drilling of composite materials with various drill bits”, *Journal of Materials Processing Technology*, vol.140, pp.335-339, 2003.

[4] C.C. Tsao and H. Hocheng, “Taguchi analysis of delamination associated with various drill bits in drilling of composite material”, International Journal of Machine Tools and *Manufacturing,* vol. 44, pp.1085-1090, 2004.

[5] Ruslan Melentiev, Paolo C. Priarone, Matteo Robiglio and Luca Settineri, “Effects of tool geometry and process parameters on delamination in CFRP drilling: An overview”, *Procedia CIRP*, vol. 45, pp.31-34, 2016.

[6] A.T. Marques, L.M. Durao, A.G. Magalhaes and J.M. Tavares, “Delamination analysis of carbon fiber reinforced laminates”, *Proceedings of the 16th International Conference on Composite Materials (ICCM -16)* held in Kyoto, Japan during July 8 -14, 2007.

[7] U.A. Khashaba, I.A. El−Sonbaty, Al Selmy and A.A. Megahed, “Drilling analysis of woven glass fiber reinforced/epoxy composites”, *Journal of Composite Materials*, vol.47, no.2, pp.191 -205, 2012.

[8] N. Koboevic, M. Jurjevic and Z. Koboevic, “Influence of cutting parameters on thrust force, drilling torque and delamination during drilling of carbon fiber reinforced composites”, *Technical Gazette*, vol.19, no.2, pp.391 -398, 2012.

[9] N. Feito, J.D. –Alvarez, A.D. –Alvarez, J.L. Cantero and M.H. Migvelez, “Experimental analysis of the influence of drill point angle and wear on the drilling of woven CFRPs”, *Materials*, vol.7, pp.4258–4271, 2014.

[10] E. Soliman, U. Kandil and M.R. Taha, “Improved strength and toughness of carbon woven fabric composites with functionalized MWCNTs”, *Materials*, vol.7, pp.4640–4657, 2014.

[11] H.F. Al–Qrimli, F.A. Mahdi and F.B. Ismail, “Carbon/epoxy woven composite experimental and numerical simulation to predict tensile performance”, *Advances in Materials Science and Applications*, vol.4, no.2, pp.33–41, 2015.

[12] M. Sahiti, M Raghavendra Reddy, Budi Joshi, J. Peter Praveen and B. Nageswara Rao, "Optimum WEDM process parameters of Incoloy®Alloy800 using Taguchi method", *International Journal of Industrial and Manufacturing Systems Engineering*, vol.1, no.3, pp.64-68, 2016

[13] P. Bharathi, T.G.L. Priyanka, G. Srinivasa Rao and B. Nageswara Rao, "Optimum WEDM process parameters of SS304 using Taguchi method", *International Journal of Industrial and Manufacturing Systems Engineering*, vol.1, no.3, pp.69-72, 2016.

[14] D. Rajeev Kumar, P.S.S.K. Varma and B. Nageswara Rao, "Optimum drilling parameters of coir fiber-reinforced polyester composites", *American Journal of Mechanical and Industrial Engineering*, vol.2, no.2, pp.92-97, 2017.

[15] M. Sahiti, M Raghavendra Reddy, Budi Joshi, and B. Nageswara Rao, "Application of Taguchi method for optimum weld process parameters of pure aluminum", *American Journal of Naval Architecture and Marine Engineering*, vol.1, no.1, pp.1-6, 2016.