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Optimizing Multi Characteristics in Drilling of GFRP Composite using Utility Concept with Taguchi's Approach

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Abstract

In the drilling process of chopped glass fibre reinforced polyester composites; the delamination is a major problem. The delamination reduces the structural integrity of the material, results in poor assembly tolerance and has the potential for long term performance deterioration. Surface roughness is also an important aspect of drilling fibre reinforced polyester which can cause high stress on rivets and bolts, leading to failure. In the modern competitive manufacturing scenario, it is very important to optimize the process parameters to arrive at its full utility. In this present study the utility concept has been applied for multi characteristics optimization and identification of the optimal setting condition of process parameters at various relative weightage values of characteristics. Delamination factor and average surface roughness were taken as the measure of performances for this material and feed rate (f), drill diameter (D), spindle speed (N) and material thickness (t) were chosen as drilling parameters. Experiments were conducted based on Taguchi L_9 (3^4) orthogonal array design. Analysis was performed based on utility method varying the importance of quality characteristics or responses in drilling process. The optimal setting of parameters is expected to be useful for process engineers.
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Keywords:Glass Fibre Reinforced Polyester composite; Delamination; Multi-response Optimization; Utility Method

1. Introduction

Fibre reinforced plastic (FRP) composites are widely used in automobile, aerospace, marine, aeronautical industries for structural applications including rocket exit nozzles, nose caps, pistons for internal combustion

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engines and fusion devices. The FRP components are superior to other materials due to their particular mechanical and physical properties such as high specific stiffness, fatigue limit, high damping, good corrosive resistance and low thermal expansion which enable the structural design more flexible than conventional metals Guu et al. (2001). The mechanism involved while cutting composite materials have been regarded as considerably distinct due to their anisotropic and non-homogenous properties Callister (2002). Drilling is usually the final operation during the assembly of the structures in aerospace and aircraft industries. It is reported that over 100,000 holes are required in a small engine aircraft, mostly for fasteners and surface roughness is an important aspect of drilling fibre reinforced plastics, which can cause high stresses on rivets and bolts leading to failure Sonbaty et al. (2004). However the delamination is the major problem associated with the drilling of fibre reinforced composite materials. Apart from reducing the structural integrity of materials the delamination also results in poor assembly tolerance and has the potential for long term performance deterioration Capello (2004). For multi-response optimization in different machining process, mostly Taguchi's methodology and Grey relational analysis has been applied Lin and Lin (2002), Sing et al. (2004), Jung and Kwon (2010), Tzeng et al. (2009), Hsu and Tsao (2008). In case of drilling response surface regression method, multivariable linear regression analysis and multi-layer feed forward ANN architecture trained using error-back propagation training algorithm were employed for the modeling Palanikumar et al. (2008), Khashaba et al. (2007), Karnik et al. (2008). A model based on Taguchi's approach and utility concept is used to predict an optimal settings of the centrifugal force assisted abrasive flow machining process parameters with the aim of the performance improvement Walia et al. (2006). There are many research works have been found for both modeling and optimization of process parameters to yield the optimum delamination and surface roughness but less work has been done varying the relative weightage of the said responses in drilling process. Thus in this investigation the optimal parameter setting conditions have been developed using utility method at different chosen weightages of responses.

2. Experimental details

2.1 Work material

The Glass Fibre Reinforced Polyester (GFRP) composite used in the experiment was supplied by VMT Glass Fiber Roofing Industries, India. Hand lay-up technique is used for producing the composite. The chopped strand mat E-glass fiber (450 g/m^2) is used as reinforcement in polyester resin to prepare the laminate. The volume fraction of the glass fiber is 0.33. Methylethyl ketone peroxide was used as the hardener during manufacturing of the composite. Tensile strength of GFRP composites is 700 kg/cm^2. The hardness of composite is Barcol 40.5. The experiments were carried out on GFRP samples of size 150 mm X 150 mm using wood as backing material.

2.2 Tool material

The HSS taper shank twist drills (Make: Addison & co. Ltd., India) confirming to IS: 5103 – 1969 /ISO: 235-1980/ DIN: 345- 1978/ BS: 328: Part 1- 1986 specifications were employed for the drilling experiments. The twist drills of 10 mm (flute length: 87 mm: overall length: 168 mm), 12mm (flute length: 100 mm: overall length: 182 mm) and 14 mm (flute length: 108 mm: overall length: 189 mm) diameters of grade M2 were employed. These drills together with different values of spindle rotation (rpm) yield different values of cutting velocity. The laminates were securely fixed on the machine table to avoid vibrations and displacements.

2.3 Equipment

The experiments were conducted on radial drilling machine (Make: The American Tool Works Co., USA). The machine is equipped with a maximum spindle speed of 1500 rpm and a variable feed from 0.1-0.625 mm/rev with a 5.5 kW motor. The maximum radial dimension of the work piece is 1475 mm.

Toolmakers' microscope with 30X magnification (Make: Carl Zeiss Ltd.) and Taylor Hobson Precision Surtronic 3+ Roughness checker were used for evaluating delamination factor and measuring surface roughness respectively.

2.4 Experimentation

In this present investigation the Taguchi based experimental design L_9 orthogonal array was used for experiment. The selected factors and their levels chosen for drilling operation of GFRP composite were tabulated in table 1. Altogether 9 numbers of experiments were conducted with the process parameters at their different levels on a radial drilling machine. The damage around the holes at the entrance was measured with a toolmakers' microscope. The delamination factor (F_d) is then determined, which is given by

$$F_d = \frac{D_{max}}{D_0} \quad (1)$$

Here D_{max} is the maximum diameter of the damaged zone, and D_0 is the diameter of the hole as shown in Fig. 1. For each test three measurements were made and the average of three values of delamination factor (F_d) was taken as the process response. The same was followed for another process response average surface roughness (R_a in microns). The experimental layout (L_9 orthogonal array) and their observed value were listed in table 2.

Table 1. Factors and levels selected for drilling of GFRP composites.

Factors	Level 1	Level 2	Level 3
Material thickness, t, (mm)	8	12	16
Drill diameter, D, (mm)	10	12	14
Spindle speed, N, (rpm)	400	800	1100
Feed rate, f, (mm/rev)	0.1	0.175	0.275

Table 2. Experimental layout and observed value

Trial	t	D	N	f	F_d	R_a(microns)
1	1	1	1	1	1.2239	3.497
2	1	2	2	2	1.2844	3.961
3	1	3	3	3	1.3257	4.633
4	2	1	2	3	1.2647	4.280
5	2	2	3	1	1.1643	3.980
6	2	3	1	2	1.2157	4.513
7	3	1	3	2	1.1743	4.171
8	3	2	1	3	1.2218	5.073
9	3	3	2	1	1.1404	4.340

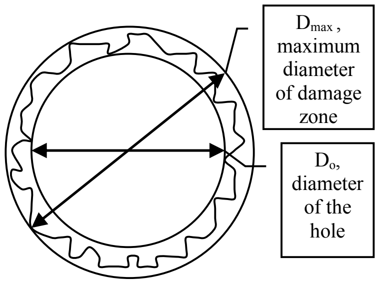

Fig.1. Scheme of the delamination factor

3. Results and analysis

3.1Utility method

The overall utility value is considered as the Process Performance Index (PPI) in the utility method for multi characteristics optimization. This method can be simplified using the following steps.

Step 1: Compute the SN ratio values for each response for all the trials.

Step 2: Determine the optimal process condition separately for each response variable using Taguchi method and then predict the optimal value for each response variable.

For a response variable, the optimal process parameters condition will be that one which maximizes the SN ratio value. The optimal SN ratio for the response variable can be determined using additive model. Suppose the optimal SN ratio for a response variable is η_{opt}. Then the optimal value V_{opt} of the smaller the best (STB) and larger the best (LTB) type response variable are obtained using equation 2 and 3 respectively.

$$V_{opt} = \sqrt{10^{-(\eta_{opt}/10)}} \tag{2}$$

$$V_{opt} = \sqrt{\frac{1}{10^{-(\eta_{opt}/10)}}} \tag{3}$$

Step 3: Determine the just acceptable values for all the response variables.

If the response variable is of STB type, its maximum observed value will be taken as the just acceptable value for the variable. On the other hand, that will be its minimum observed value if the variable is of LTB type.

Step 4: Construct the preference scale for each response variable.

To determine the utility value for response variables, a preference scale for each attribute or response variable is constructed. Two arbitrary numerical values (preference number) 0 and 9 are assigned to the just acceptable and the best value of the response variable respectively. The preference number P_i for i^{th} response variable can be expressed on a logarithmic scale as follows

$$P_i = A_i \times \log\left(\frac{y_i}{y_i^*}\right) \tag{4}$$

Where y_i = value of i^{th} response variable, y_i^* = just acceptable value of i^{th} response variable and A_i = constant for i^{th} response variable. The value of A_i can be found by the condition that if $y_i = y_{opt}$ (where y_{opt} is the optimal or best value for i^{th} response), then $P_i = 9$. Therefore

$$A_i = \frac{9}{\log\left(\frac{y_{opt}}{y_i^*}\right)} \tag{5}$$

Step 5: Determine the overall utility value for each trial using given equation.

$$U = \sum_{i=1}^{p} W_i P_i \quad (6)$$

Subject to the condition that $\sum_{i=1}^{p} W_i = 1$, where W_i is the weightage value of i^{th} response and P_i is the preference number which is found out from equation 4.

Step 6: Use arithmetic average to calculate the factor effects on the overall utility value and then decide the optimal factor level combination by higher the better factor effects.

According to Taguchi, the derived optimal process parameters condition must be validated before implementation. This is because if the model assumption is not appropriate, the selected optimal factor level combination may be erroneous due to which the expected results will not be achieved. The proposers of the method has, therefore, recommended to predicted the expected results at the derived optimal condition using additive model, carry out an experimental trial with the optimal factor level combination and then compare the actual results with the predicted ones.

Based upon the above methodology the Taguchi's analysis has been considered to obtain the optimal settings of the process parameters for individually delamination factor and average surface roughness. The optimal settings were determined for both the responses separately as shown in tables through 3 to 8 including ANOVA table and corresponding main effect plot.

Table 3. SN ratio values of responses (F_d and R_a)

Trial	Delamination factor (F_d)	Average surface roughness (R_a)
1	-1.75492	-10.8739
2	-2.17401	-11.9561
3	-2.44891	-13.3172
4	-2.03975	-12.6289
5	-1.32130	-11.9977
6	-1.69653	-13.0893
7	-1.39558	-12.4048
8	-1.7400	-14.1053
9	-1.14114	-12.7498

Table 4. Response table for means of F_d

Factor	Level 1	Level 2	Level 3
t	1.2780	1.2149	1.1788
D	1.2209	1.2235	1.2273
N	1.2205	1.2298	1.2214
f	1.1762	1.2248	1.2707
Overall mean = 1.2239			

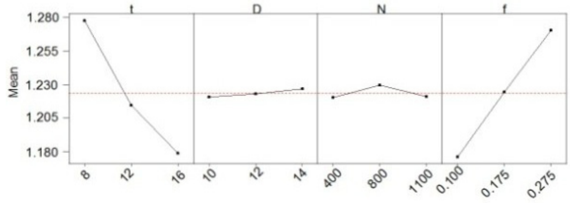

Fig. 2. Main effect plot for F_d

Table 5. Response table for means of R_a

Factor	Level 1	Level 2	Level 3
t	4.03	4.258	4.528
D	3.983	4.338	4.495
N	4.361	4.194	4.261
f	3.939	4.215	4.662
Overall mean = 4.272			

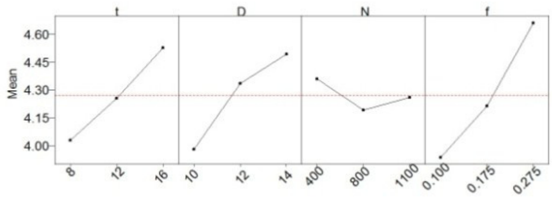

Fig.3. Main effect plot for R_a

Table 6. pooled ANOVA table for F_d based on experimental data

Factor	DOF	Sum of Square	Variance	Calculated F value
t	2	0.0151164	0.0075582	250.71
(D)	(2)	(0.0000603)		Pooled
N	2	0.0001592	0.0000796	2.64
f	2	0.0134084	0.0067042	222.38
E(pooled)	2	0.0000603	0.0000301	
Total	8	0.0287443		

Table 7. Pooled ANOVA table for R_a based on experimental data

Factor	DOF	Sum of Square	Variance	Calculated F value
t	2	0.37243	0.18622	8.76
D	2	0.41384	0.20692	9.73

(N)	(2)	(0.04251)		Pooled
f	2	0.79871	0.39936	18.79
E(pooled)	2	0.04251	0.02126	
Total	8	1.62750		

Table 8. Individual optimal setting and predicted values of process parameters

Response characteristics	Optimal combination of factors	Predicted optimal value of responses
F_d	$t_3D_1N_3f_1$	1.128
R_a	$t_1D_1N_2f_1$	3.399

As the aim of investigation was to minimize the value of responses (F_d and R_a), the optimal values were predicted using the equation no 2 and finally the summary results are given in table 8. Now construct the preference scale using equation no 4 for F_d and R_a. In case of delamination factor just acceptable value, $y_i^* = 1.3257$ (max. Observed value); optimal value, $y_{opt} = 1.128$ (refer Table 8) and the constant taken as A = -128.32 and for average surface roughness the corresponding values have been taken as $y_i^* = 5.073$ (max. Observed value), $y_{opt} = 3.399$ (refer Table 8) and A = -51.75. The calculated preference scale for process responses at each trial produced in table 9.

Table 9. Preference scale of responses

Trial	Preference Scale	
	F_d	R_a
1	4.4526	8.3612
2	1.7637	5.5610
3	0	2.0391
4	2.6251	3.8202
5	7.2347	5.4535
6	4.8272	2.6288
7	6.7581	4.4000
8	4.5483	0
9	8.3906	3.5074

In respect of importance of performance characteristics varying the weightage values for both responses delamination factor and average surface roughness such that the summation of weightage of responses should be one, the overall utility values have been calculated using equation 6 and calculated values shown in table 10. However, these weightage values can be varied depending upon the case or customer requirements, if any. Thereafter optimal factor level combinations have been determined at assigned weightage of responses as shown in table 11.

Table 10. Calculated overall utility value based on responses at assign weightage

Trial	WF_d=0.25 WR_a=0.75	WF_d=0.5 WR_a=0.5	WF_d=0.75 WR_a=0.25
1	7.3840	6.4069	5.4297
2	4.6117	3.6624	2.7130
3	1.5293	1.0196	0.5098
4	3.5214	3.2227	2.9239
5	5.8988	6.3441	6.7894
6	3.1784	3.7280	4.2776
7	4.9895	5.5791	6.1686
8	1.1371	2.2741	3.4112
9	4.7282	5.9489	7.1698

Table 11. Effect of factor level of overall utility at assigned weightage of responses

Factor	WF_d=0.25 WR_a=0.75			WF_d=0.5 WR_a=0.5			WF_d=0.75 WR_a=0.25		
	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
t	4.5083	4.1995	3.6183	3.6963	4.4316	4.6007	2.8842	4.6636	5.5832
D	5.2983	3.8825	3.1453	5.0696	4.0935	3.5655	4.8407	4.3045	3.9857
N	3.8998	4.2871	4.1392	4.1363	4.2780	4.3143	4.3728	4.2689	4.4893
f	6.0037	4.2599	2.0626	6.2333	4.3232	2.1721	6.4629	4.3864	2.2816
	Optimal process parameters combination : $t_1D_1N_2f_1$			Optimal process parameters combination : $t_3D_1N_3f_1$			Optimal process parameters combination : $t_3D_1N_3f_1$		

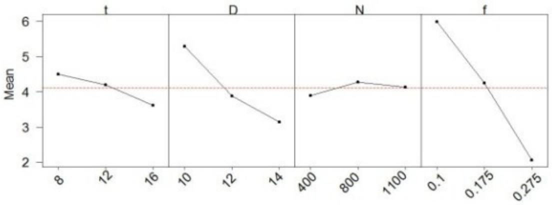

Fig. 4. Main effect plot of Utility data at WF_d=0.25 and WR_a=0.75

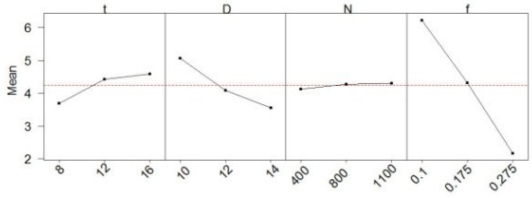

Fig.5. Main effect plot of Utility data at WF_d=0.5 and WR_a=0.5

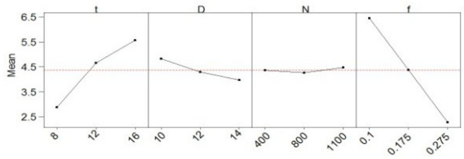

Fig.6. Main effect plot of Utility data at WF_d=0.75 and WR_a=0.25

It is clear from, table 11 effect of factor level for overall utility at assigned weightage that the optimal process parameters combination is $t_1D_1N_2f_1$ when weightage of delamination factor is 25% and average surface roughness is 75%. Similarly at 75% and 25% weightage of delamination factor and average surface roughness respectively the optimal process parameters combination is $t_3D_1N_3f_1$. Also it shows the same optimal combination of process parameters at equal weightage of both the responses. The optimal process parameters combination is yield a maximum value of the overall utility function of the process or product within the experimental space for multi response optimization in drilling of GFRP composite material.

Table 12. Pooled ANOVA table of utility data at WF_d=0.25 WR_a=0.75

Source	DOF	SS	V	F	%contribution
t	2	1.2254	0.6127	5.35	3.82%
D	2	7.1833	3.5917	31.35	22.42%
N	(2)	(0.2291)	(0.1146)		------
f	2	23.4008	11.7004	102.12	73.04%
E(pooled)	2	0.2291	0.1146		0.715%
Total	8	32.0387			

Table 13. Pooled ANOVA table of utility data at WF_d=0.5 WR_a=0.5

Source	DOF	SS	V	F	%contribution
t	2	1.3873	0.6936	26.15	4.67%
D	2	3.4935	1.7468	65.85	11.76%
N	(2)	(0.0531)	(0.0265)		------
f	2	24.7690	12.3845	466.88	83.39%
E(pooled)	2	0.0531	0.0265		0.178%
Total	8	29.7029			

Table 14. Pooled ANOVA table of utility data at WF_d=0.75 WR_a=0.25

Source	DOF	SS	V	F	%contribution
t	2	11.2969	5.6484	154.92	29.18%
D	2	1.1202	0.5601	15.36	2.89%
N	(2)	(0.0729)	(0.0364)		------
f	2	26.2257	13.1129	359.65	67.74%
E(pooled)	2	0.0729	0.0364		0.188%
Total	8	38.7157			

Table 15. Average value of responses at optimal level based on table 2.

Responses	WF_d=0.25 WR_a=0.75				WF_d=0.5 WR_a=0.5				WF_d=0.75 WR_a=0.25			
	t_1	D_1	N_2	f_1	t_3	D_1	N_3	f_1	t_3	D_1	N_3	f_1
(F_d)	1.2780	1.2209	1.2298	1.1762	1.1788	1.2209	1.2214	1.1762	1.1788	1.2209	1.2214	1.1762
(R_a)	4.03	3.983	4.194	3.939	4.528	3.983	4.261	3.939	4.528	3.983	4.261	3.939

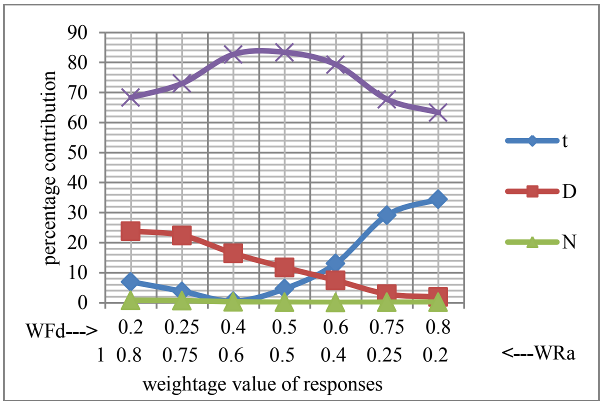

Fig.7. Variation of percentage contribution of process parameters

The pooled version ANOVA for utility data indicates that the process parameters such as material thickness (t), drill diameter (D) and feed rate (f) are significant at 95% confidence level and their corresponding percentage contribution. Since the spindle speed (N) is insignificant so it can be taken as economy factor.

The percentage contribution or importance of process parameters in drilling operation of GFRP composite material have been studied for multiresponse optimization with varying the weightage of responses. Fig 7 implies that spindle speed (N) is less importance for in this case. While feed rate (f) is most important parameter. Percentage contribution of feed increases at certain level of weightage of delamination factor afterwards it decreases with increasing of weightage of delamination factor. Percentage contribution of material thickness will be high at less weightage of surface roughness.

3.2 Predicted mean and optimal range for responses

The predicted mean value of various response characteristics (μ_R) at optimal process parameters combination can be obtained from the following relation

$$\mu_R = \sum_{i=1,j=1}^{n,m} P_{i,j} - (n-1)M_R \tag{7}$$

Where μ_R is predicted mean response, $P_{i,j}$ is the ith parameter jth level, i = 1,2,3,......,n and j = 1,2,3,.......,m and M_R is the overall mean value of response characteristics. The 95% confidence interval of confirmation experiment (CI_{CE}) can be calculated by using the following equation Kumar et al. (2000).

$$CI_{CE} = \sqrt{F_{\propto}(1, f_e)V_e\left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \tag{8}$$

Where, $F_{\propto}(1, f_e)$ = F ratio at a confidence level of (1- α) against DOF 1 and error degree of freedom (f_e) , V_e= Error variance, $n_{eff} = N/(1+DOF)$, N is the total number of experiment (trial) and DOF is the degrees of freedom associated in the estimate of mean response, R = sample size for confirmation experiment. In this study varying the weightage of responses the optimal process parameters combinations obtained through utility concept are $t_1D_1N_2f_1$ (WF_d=0.25, WR_a=0.75) and $t_3D_1N_3f_1$ (WF_d=0.5, WR_a=0.5 & WF_d=0.75, WR_a=0.25). The details have been shown in tabulated form through table 9 to 14 and corresponding main effect plot shown in Fig 4 to 6.

(a)For delamination factor (F_d) at WF_d=0.25, WR_a=0.75

$$\mu_{F_d} = t_1 + D_1 + N_2 + f_1 - 3M_{F_d} = 1.2332$$

Where $t_1 = 1.2780$, $D_1 = 1.2209$, $N_2 = 1.2298$, $f_1 = 1.1762$ an $M_{F_d} = 1.2239$d from table 4 and 15. The following values have been obtained from the ANOVA table (Table 6). $F_{0.05}(1,2) = 18.51$ (Tabulated F value),$V_e = 0.0000301$ $N = 9$, $n_{eff} = 1.286$ (calculated) , $R = 3$ thereafter using equation 8 we obtain $CI_{CE} = \pm 0.0248$
Thus the predicted optimal range for delamination factor (F_d) is $1.2084 < \mu_{F_d} < 1.258$

(b)For average surface roughness (R_a) at WF_d=0.25, WR_a=0.75

$$\mu_{R_a} = t_1 + D_1 + N_2 + f_1 - 3M_{R_a} = 3.330$$

Where $t_1 = 4.03$, $D_1 = 3.983$, $N_2 = 4.194$, $f_1 = 3.939$ and $M_{R_a} = 4.272$ from table 5 and 15. The following values have been obtained from the ANOVA table (Table 7). $F_{0.05}(1,2) = 18.51$(Tabulated F value), $V_e = 0.02126$, $N = 9$, $n_{eff} = 1.286$ (calculated) , $R = 3$ thereafter using equation 8 we obtain $CI_{CE} = \pm 0.6612$
Thus the predicted optimal range for average surface roughness (R_a) is $2.669 < \mu_{R_a} < 3.991$

Similarly at WF_d=0.5, WR_a=0.5 the predicted value and optimal range found out of delamination factor and average surface roughness respectively are given below. Also it shows the same at WF_d=0.75, WR_a=0.25 weightage value.

(c)For delamination factor (F_d):

$$\mu_{F_d} = t_3 + D_1 + N_3 + f_1 - 3M_{F_d} = 1.1256$$

The predicted optimal range for delamination factor (F_d) is $1.2084 < \mu_{F_d} < 1.258$

(d)For average surface roughness (R_a):

$$\mu_{R_a} = t_3 + D_1 + N_3 + f_1 - 3M_{R_a} = 3.895$$

The predicted optimal range for average surface roughness (R_a) is $3.234 < \mu_{R_a} < 4.556$

4. Confirmation test

Three experiments were performed at optimal settings (for multi-responses) of process parameters in drilling of GFRP composite for confirmation test, as suggested by Taguchi analysis of utility method. The measured values of chosen response characteristics have been tabulated in table 16. It shows that the overall average of the measured or observed values of responses (F_d and R_a) are varied within the predicted optimal range of the respective responses at the 95% confidence interval of confirmation test. The percentage deviation of delamination factor among experimental overall mean (confirmation test) and estimated mean lies within more or less 1.5% while weightage of responses varying from 0.25 to 0.75 such that summation of responses is one and for average surface roughness that lies within 6.5%. But at same weightage of responses (F_d and R_a) and 0.75 and 0.25 weightage of delamination factor (F_d) and average surface roughness (R_a) respectively, it gives close result to each other among experimental overall mean and estimated mean. Thus it proves the validation of obtained optimal process parameters combination for multi characteristics optimization in drilling of Glass Fibre Reinforced Polyester composite material at various weightage values of performance characteristics.

Table 16. Confirmation test results

Exp. no.	WF_d=0.25 WR_a=0.75		WF_d=0.5 WR_a=0.5		WF_d=0.75 WR_a=0.25	
	Delamination factor (F_d)	Average surface roughness (R_a)	Delamination factor (F_d)	Average surface roughness (R_a)	Delamination factor (F_d)	Average surface roughness (R_a)
1	1.2145	3.707	1.1387	3.513	1.1387	3.513
2	1.2239	3.497	1.1225	3.871	1.1225	3.871
3	1.2073	3.473	1.1402	4.103	1.1402	4.103
Experimental overall mean	1.2152	3.559	1.1338	3.829	1.1338	3.829
Estimated mean	1.2332	3.330	1.1256	3.895	1.1256	3.895
% deviation	1.48	6.43	0.72	1.72	0.72	1.72

5. Conclusion

A simplified model based on Taguchi's approach and utility concept is used to develop the optimal combination of process parameters with varying the weightage of responses for multi characteristics optimization in drilling of glass fibre reinforced polyester composite material for use of process engineers. In this study, for multi characteristics optimization the experimental results, obtained through the developed optimal process parameters combination, are within the predicted specified range of both the responses delamination factor and average surface roughness. It shows the validation of the developed process parameters combination for the above work. Among all the chosen parameters in drilling of GFRP composite material the spindle speed is insignificant but the feed rate is highly significant and effective then drill diameter and material thickness.

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