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ORIGINAL ARTICLE

Optimisation of machining parameters of glass-fibre-reinforced plastic (GFRP) pipes by desirability function analysis using Taguchi technique

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Abstract This paper presents a new approach for optimizing the machining parameters on turning glass-fibre-reinforced plastic (GFRP) pipes. Optimisation of machining parameters was done by an analysis called desirability function analysis, which is a useful tool for optimizing multi-response problems. In this work, based on Taguchi's L_{18} orthogonal array, turning experiments were conducted for filament wound and hand layup GFRP pipes using K_{20} grade cemented carbide cutting tool. The machining parameters such as cutting velocity, feed rate and depth of cut are optimized by multi-response considerations namely surface roughness, flank wear, crater wear and machining force. A composite desirability value is obtained for the multi-responses using individual desirability values from the desirability function analysis. Based on composite desirability value, the optimum levels of parameters have been identified, and significant contribution of parameters is determined by analysis of variance. Confirmation test is also conducted to validate the test result. It is clearly shown that the multi-responses in the machining process are improved through this approach. Thus, the application of desirability function analysis in Taguchi technique proves to be an effective tool for optimizing the machining parameters of GFRP pipes.

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Nomenclature

V	Cutting Velocity in m/min
f	Feed rate in mm/rev
d	Depth of cut in mm
R_a	Surface roughness value in μm
FW	Flank wear in mm
CW	Crater wear in mm
DOE	Design of experiments
Wt	Weightage
TCN	Test condition number
d_i	Individual desirability for responses
d_G	Composite desirability

1 Introduction

Glass-fibre-reinforced plastic (GFRP), an advanced polymeric matrix composite material, is widely used in a variety of applications which includes aircraft, robots and machine tools [1]. High dimensional accuracy and better surface integrity are the necessary qualities of the machined surfaces of GFRP [2]. Generally, GFRP composite pipes are manufactured either by hand layup process or by filament winding method. Near net-shaped components with the required surface finish quality can be manufactured by subsequent machining processes [3]. Machining techniques of fibre-reinforced plastic (FRP) were initially developed from either textile cutting, which are suited for prepregs, or from wood working and metal working processes [4]. Machining of fibre-reinforced composite differs significantly from machining of conventional metals and alloys, owing to the behaviour of matrix material, reinforcement and diverse properties of fibre, matrix and orientation of fibre and volume fraction of fibres [5].

A new machinability index was proposed by Paulo Davim and Mata [6, 7] for the turning of hand laid up GFRP materials using polycrystalline diamond (PCD) and cemented carbide (K15) cutting tools. The investigation reveals that the PCD tool performs well compared to cemented carbide (K15) tool in terms of surface roughness and specific cutting pressure. Fibre orientation is a key factor that determines the surface integrity of a machined surface and 90° is a critical angle, beyond which a severe subsurface damage will occur. If the fibre orientation angle is greater than 90°, the three distinct deformation zones appear, namely chipping, pressing and bouncing [8]. Yang and Tarng [9] used the Taguchi method to find the optimal cutting parameters in turning operations. Palanikumar and Paulo Davim [10] developed a mathematical model to predict the tool wear on machining of glass-fibre-reinforced composite. Regression analysis and analysis of variance were used to develop the model. Palanikumar et al. [11] have also attempted to assess the influence of machining parameters on surface roughness in machining GFRP composites. It concludes that the feed rate has more influence on surface roughness and it is followed by cutting speed. Evaluation of cutting parameters and the influence of matrix under cutting force, delamination factor and surface roughness in two types of polyester thermoset matrix material such as Viapal (VUP 9731) and ATLAC (382-05) was carried out with cemented carbide (K10) drill for machining FRP by Paulo Davim et al. [12]. Ramkumar et al. [13] attempted a newer technique of superimposing oscillatory vibration to minimise the damage arising during the drilling of GFRP composites. Arul et al. [14] experimentally investigated the parametric influence on cutting force.

Machining force also plays a key role in analysing the machining process of FRPs. The value of machining force in the work piece is determined using the equation $F_{\mathrm{m}} = \sqrt{Fx^2 + Fy^2 + Fz^2}$. Generally, machining force increases with feed rate and decreases with cutting velocity [15]. Evaluation of machining parameters of hand layup GFRP related to machining force was also carried out by Paulo Davim et al. [16] on milling using cemented carbide (K_{10}) end mill. Singh and Bhatnagar [17] made an attempt to correlate the drilling-induced damage with the drilling parameters of unidirectional GFRP composite laminates. Mohan et al. [18] analysed the influence of machining parameters on cutting force during drilling of glass-fibre-reinforced composite with the help of a commercially available software package MINITAB14. Similarly, the influence of tool materials and tool geometries on cutting characteristics of glass-fibre-reinforced plastic was investigated by An et al. [19]. According to the authors, a tool with a straight edge performs better than a tool having a round edge. Lee [20] investigated the machinability of GFRP using tools of various materials and geometries. Ramkumar et al. [21] investigated the effect of workpiece vibration on drilling GFRP laminates. By vibrating the workpiece, it was observed that there could be a considerable amount of reduction in thrust force, tool wear, temperature, power and the surface roughness. A study on determining the effective hardness of tool material at which steady machining can be performed was carried out by Sreejith et al. [22]. The cutting speed has a large influence on carbide tool wear/life. The tool wear has a strong influence on feed force and surface roughness [23]. Carbide tools offer better surface finish of acceptable range at a lower cost. It is inferred that the feed rate has more influence than the cutting velocity on surface finish [3]. Turning tests on GFRP rods were carried out by Bagci and Isik [24] using cemented carbide cutting tools. Fibre orientation plays a vital role in the surface roughness during cutting. Peaks of roughness are generated with 0° cut. Owing to the combined load of bending and compression at 45° cut, fibres are pulled out by kinking and breaking which resulted in poorest surface quality. Smoothened surface can be obtained through 90° cut [3]. Palanikumar [25] used Taguchi's method and response surface methodologies for minimising surface roughness in machining GFRP using polycrystalline diamond tool. Paulo Davim [26] attempted to study the influence of cutting conditions on surface roughness during turning by design of experiments and regression analysis. Aravindan et al. [27] investigated the machinability of hand layup GFRP pipes using statistical techniques.

Almost all the attempts to study the machining characteristics and its optimisation are based on traditional approaches such as analysis of variance (ANOVA), regression analysis and by using other mathematical models. Therefore, this paper presents a new approach to optimise the machining characteristics of GFRP pipes using desirability function analysis (DFA). DFA is one of the most widely used methods in industry for the optimisation of multi-response characteristics [28]. Desirability function analysis is used to convert the multi-response characteristics into single-response characteristics. As a result, optimisation of the complicated multi-response characteristics can be converted into optimisation of a single-response characteristic termed composite desirability. It does not involve complicated mathematical theory or computation like in traditional approaches and thus can be employed by the engineers without a strong statistical background. The multi-responses such as surface roughness, machining force and tool wear are combined as composite desirability using desirability function analysis.

This method simplifies the identification of operating conditions that provide the 'most desirable' responses. In short, there is an ample scope of applying the proposed methodology of desirability function analysis in the Taguchi method for the optimisation of machining parameters of turning GFRP pipes using cemented carbide K_{20} grade cutting tool. Both filament wound as well as hand layup GFRP pipes are considered in this study. The optimised results are also subjected to validation for confirmation.

2 Experimental details

2.1 Materials and processes

GFRP pipes were made using the resin composition of isophthalic (50%) and vinylester (50%). The volume fraction of the materials is 65:35 (resin/glass). Table 1 shows the mechanical and thermal properties of the selected GFRP pipes. The fibre orientation angle of the specimen used for the tests is 90°. The structural orientation of the specimen used for the tests is SM + 18CSM + SM, where SM is the surface mat and CSM is the chopped strand mat. The hand layup pipe composite specimens were of 75 mm length and 30 and 55 mm of inner and outer diameters, respectively. The filament wound composite specimens were of 75 mm length and 35 and 65 mm of inner and outer diameters, respectively. A CNC lathe (FANUC) with 7.5 kW spindle power and maximum speed of 4,500 rpm was used to perform the machining operation. The force measurement was carried out using a Kistler dynamometer. The data acquisition was carried out by appropriate software called *Dynaware kistler* as presented in Fig. 1.

Coated carbide tool inserts (K_{20} grade) were used for machining. The cutting tool inserts used for the machining are of readily available Kennametal make. The geometry of the cutting tool insert is as follows: rake angle −7° (negative), 7° clearance angle, 80° edge major tool cutting, 0° cutting edge inclination angle and nose radius of 0.8 mm. Tool wear was measured using passing and reflection type tool maker's microscope having a least count of 0.5 μm. Flank wear was measured by the width of wearland on the flank below the cutting edge. The crater wear was measured by the depth of cup in the rake face. The surface roughness was evaluated using a surface roughness measuring instrument of Kosaka Lab, Japan. The cutoff length of the instrument is 0.80 mm.

Table 1 Mechanical and thermal properties of the GFRP materials

Mechanical and thermal properties	Value	
	Hand layup	Filament winding
Long-term hydrostatic strength (MPa)	95	140
Short-term hydrostatic strength (MPa)	150	240
Tensile modulus (MPa)	169.75	280
Tensile strength (MPa)	60	95
Coefficient of linear expansion (m/m °C)	2×10^{-5}	2×10^{-5}
Thermal conductivity (W/m K)	0.29	0.29
Density (kg/m$^{3)}$	1260	1800

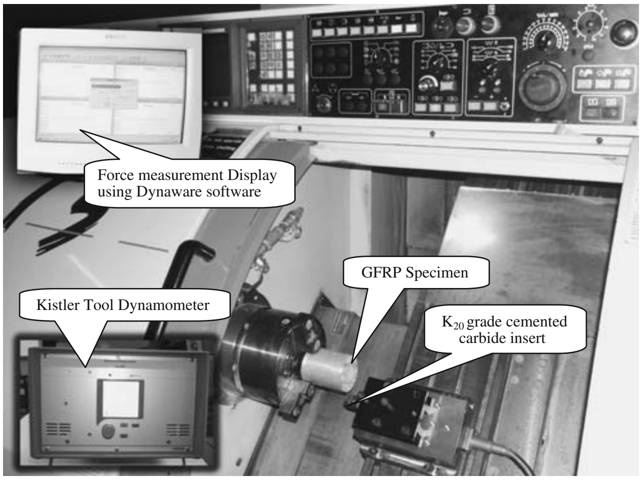

Fig. 1 Set up of CNC lathe with the Kistler dynamometer

2.2 Plan of experiments

Robust design is an engineering methodology for obtaining product and process conditions which are minimally sensitive to the various causes of variation to produce high-quality products with low development and manufacturing costs [29]. Taguchi's parameter design is an important tool for robust design. It offers a simple and systematic approach to optimise design for performance, quality and cost. Taguchi methods which combine the experiment design theory and the quality loss function are applied to the robust design of products and process. The method had solved even complex problems in manufacturing. Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments [30].

The methodology of Taguchi for three factors at three levels is used for the implementation of the plan of experiments. The factors and levels assumed are tabulated in Table 2. The orthogonal array L_{18} is selected as shown in Table 3, which has 18 rows corresponding to the number of tests with the required columns. The plan of experiments comprises 18 tests where the second column is assigned to the cutting velocity (V), the third column is assigned to the feed rate (f) and the fourth is to the depth of cut (d). Both hand layup and filament wound pipes were machined using

Table 2 Factors and levels

Parameters	Unit	Levels		
		1	2	3
Cutting velocity (*V*)	m/min	100	150	200
Feed rate (*f*)	mm/rev	0.05	0.1	0.2
Depth of cut (*d*)	mm	0.5	1.0	2.0

L_{18} orthogonal array separately with the same machining parameters for each of the 18 test conditions. The quality characteristics to be studied are machining force, flank wear, crater wear and surface roughness. The experimentally collected data are then subjected to optimisation using ANOVA obtained from desirability function analysis.

2.3 Optimisation steps using desirability function analysis in the Taguchi method

Step 1: Calculate the individual desirability index (d_i) for the corresponding responses using the formula proposed by the Derringer and Suich [28]. There are three forms of the desirability functions according to the response characteristics.

(a) The-nominal-the best: The value of $\widehat{y}$ is required to achieve a particular target *T*. When the $\widehat{y}$ equals to *T*, the desirability value equals to 1; if the departure of $\widehat{y}$ exceeds a particular range from the target, the desirability value equals to 0, and such situation represents the worst case. The desirability function of the nominal-the-best can be written as given in Eq. 1:

$$d_i = \begin{cases} \left(\frac{\widehat{y}-y_{\min}}{T-y_{\min}}\right)^s, & y_{\min} \le \widehat{y} \le T,\ s \ge 0 \\ \left(\frac{\widehat{y}-y_{\max}}{T-y_{\max}}\right)^t, & T \le \widehat{y} \le y_{\max},\ t \ge 0 \\ 0, & \end{cases} \quad (1)$$

where the $y_{\max}$ and $y_{\min}$ represent the upper/lower tolerance limits of $\widehat{y}$ and *s* and *t* represent the weights.

(b) The-larger-the better: The value of $\widehat{y}$ is expected to be the larger the better. When the $\widehat{y}$ exceeds a particular criteria value, which can be viewed as the requirement, the desirability value equals to 1; if the $\widehat{y}$ is less than a particular criteria value, which is unacceptable, the desirability value equals to 0. The desirability function of the-larger-the better can be written as given in Eq. 2:

$$d_i = \begin{cases} 0, & \widehat{y} \le y_{\min} \\ \left(\frac{\widehat{y}-y_{\min}}{y_{\max}-y_{\min}}\right)^r & y_{\min} \le \widehat{y} \le y_{\max}, r \ge 0 \\ 1, & \widehat{y} \ge y_{\min} \end{cases} \quad (2)$$

where the $y_{\min}$ represents the lower tolerance limit of $\widehat{y}$, the $y_{\max}$ represents the upper tolerance limit of $\widehat{y}$ and *r* represents the weight.

Table 3 Experimental test conditions and observed data

Test condition Number	Speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Filament wound pipes				Hand layup pipes			
				Flank Wear (mm)	Crater Wear (mm)	R_a (μm)	F_m(*N*)	Flank Wear (mm)	Crater Wear (mm)	R_a (μm)	F_m (*N*)
1	100	0.05	0.5	0.059	0.011	2.35	57.23	0.023	0.018	3.95	17.50
2	100	0.1	1	0.066	0.009	4.06	83.18	0.018	0.048	8.21	47.50
3	100	0.2	2	0.088	0.007	3.95	95.68	0.028	0.018	6.22	17.50
4	150	0.05	0.5	0.068	0.009	2.81	51.78	0.017	0.018	4.25	17.70
5	150	0.1	1	0.078	0.008	3.61	77.47	0.048	0.015	8.52	15.00
6	150	0.2	2	0.109	0.006	3.65	86.48	0.025	0.015	5.03	15.00
7	200	0.05	1	0.085	0.007	3.71	71.48	0.018	0.008	6.07	7.50
8	200	0.1	2	0.108	0.006	4.07	68.14	0.018	0.013	6.07	12.50
9	200	0.2	0.5	0.112	0.006	3.67	43.98	0.023	0.012	6.34	11.50
10	100	0.05	2	0.067	0.009	3.63	58.24	0.025	0.013	4.73	12.80
11	100	0.1	0.5	0.064	0.010	2.87	50.39	0.020	0.030	6.14	30.00
12	100	0.2	1	0.079	0.008	3.13	47.91	0.020	0.023	7.51	22.50
13	150	0.05	1	0.071	0.009	3.88	74.57	0.025	0.025	3.81	25.00
14	150	0.1	2	0.087	0.007	2.74	83.32	0.016	0.013	4.03	12.50
15	150	0.2	0.5	0.090	0.007	3.39	69.61	0.015	0.008	3.73	7.50
16	200	0.05	2	0.096	0.007	3.26	132.97	0.023	0.008	4.41	8.00
17	200	0.1	0.5	0.089	0.007	2.58	40.66	0.028	0.018	8.12	17.50
18	200	0.2	1	0.122	0.005	3.99	66.29	0.023	0.012	5.08	12.00

(c) The-smaller-the better: The value of $\widehat{y}$ is expected to be the smaller the better. When the $\widehat{y}$ is less than a particular criteria value, the desirability value equals to 1; if the $\widehat{y}$ exceeds a particular criteria value, the desirability value equals to 0. The desirability function of the-smaller-the-better can be written as given in Eq. 3:

$$d_i = \begin{cases} 1, & \widehat{y} \leq y_{\min} \\ \left(\frac{\widehat{y}-y_{\max}}{y_{\min}-y_{\max}}\right)^r, \quad y_{\min} \leq \widehat{y} \leq y_{\max}, & r \geq 0 \\ 0, & \widehat{y} \geq y_{\max} \end{cases} \tag{3}$$

where the $y_{\min}$ represents the lower tolerance limit of $\widehat{y}$, the $y_{\max}$ represents the upper tolerance limit of $\widehat{y}$ and r represents the weight. The s, t and r in Eqs. 1, 2 and 3 indicate the weights and are defined according to the requirement of the user. If the corresponding response is expected to be closer to the target, the weight can be set to the larger value; otherwise, the weight can be set to the smaller value.

In this study, “the smaller the better” characteristic is applied to determine the individual desirability values for tool wear, machining force and surface roughness since all responses are to be minimised.

Step 2: Compute the composite desirability (d_G). The individual desirability index of all the responses can be combined to form a single value called composite desirability (d_G) by the following Eq. 4:

$$d_G = \sqrt[w]{\left(d_1^{w_1} * d_2^{w_2} \ldots\ldots\ldots\ldots * d_i^{w_i}\right)} \tag{4}$$

where d_i is the individual desirability of the property Y_i, w_i is the weight of the property “Y_i” in the composite desirability and w is the sum of the individual weights.

Step 3: Determine the optimal parameter and its level combination. The higher composite desirability value implies better product quality. Therefore, on the basis of the composite desirability (d_G), the parameter effect and the optimum level for each controllable parameter are estimated.

Step 4: Perform ANOVA for identifying the significant parameters. ANOVA establishes the relative significance of parameters. The calculated total sum of square values is used to measure the relative influence of the parameters.

Step 5: Calculate the predicted optimum condition. Once the optimal level of the design parameters has been selected, the final step is to predict and verify the quality characteristics using the optimal level of the design parameters.

3 Results and discussion

The machinability in this work was evaluated by surface roughness (R_a) of the machined surface of the work piece, machining force and tool wear. Both flank wear as well as crater wear are considered, and the results obtained through experiments are also presented in Table 3.

The Taguchi’s design of experiments and desirability function analysis are applied in this work for the identification of best levels of cutting parameters, significance, and optimisation of parameters. By considering the cutting velocity, feed rate and depth of cut, the minimum number of set of experiments required was calculated as 18, and the experiments were conducted with different cutting inserts of the same specification. A cutting tool insert with maximum wear is shown in Fig. 2. Three factors at three levels each are considered here, and hence, L_{18} orthogonal array was selected. Machining of GFRP is continued with the same insert up to a maximum material removal of 30,000 mm^3. For such constant volume of material removal, the tool wear, machining force and surface finish are measured under different machining conditions.

The Taguchi’s approach to experimental design is described below. The first step in the Taguchi method is to determine the quality characteristic which is to be optimised. The output or response variable which influence effectively on the quality of product is known as quality characteristic. In this study, the tool wear, machining force and surface roughness are the quality characteristics. In the second step, the control parameters or test parameters which have significant effects on the quality characteristic are identified with the required number of levels. In the third step, the appropriate orthogonal array for the control parameters is selected after calculating the minimum number of experiments required to be conducted by considering the interactive effects. The experimental test conditions are shown in Table 3. In order to get good surface quality and dimensional properties, it is necessary to employ optimisation techniques to find optimal cutting

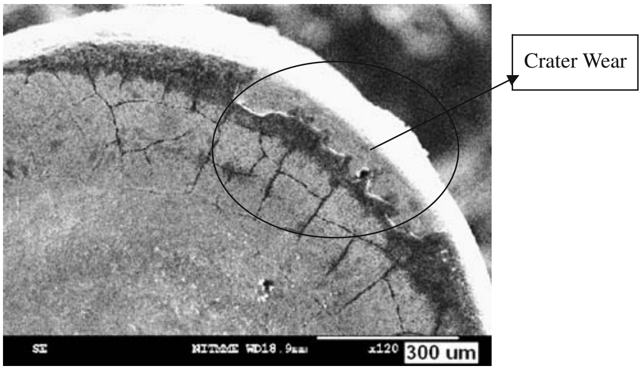

Fig. 2 SEM photograph for tool wear

parameters and theoretical models to do predictions [25]. Taguchi and desirability function analysis can be conveniently used for these purposes, and hence, the aforementioned methodologies are opted to optimise the machining parameters in this work.

3.1 Implementation of the methodology

Step 1: The individual desirability (d_i) is calculated for all the responses depending upon the type of quality characteristics. Since all the responses are possessing minimisation objective, the equation corresponding to smaller the better type is selected. The computed individual desirability for each quality characteristics using Eq. 3 are shown in Table 4.

Step 2: The composite desirability values (d_G) are calculated using Eq. 4. The weightage for responses are based on assumed weightage of 1:2:3:4 for crater wear, flank wear, machining force and surface roughness, respectively. Finally, these values are considered for optimising the multi-response parameter design problem. The results are given in the Table 4.

Step 3: From the value of composite desirability in Table 4, the parameter effect and the optimal level are estimated. The results are tabulated in Tables 5 and 6, and parameter effects are plotted in Figs. 3 and 4. Considering the maximisation of composite desirability value, the optimal parameter condition is obtained as $V_2f_2d_1$ for filament wound pipes and $V_2f_1d_3$ for hand layup pipes.

Step 4: Using the composite desirability value, ANOVA is formulated for identifying the significant parameters. The results of ANOVA are given in the Tables 7 and 8 for filament wound pipes and hand layup pipes, respectively.

Step 5: Prediction of optimum condition: By using the identified optimal parameter condition, the quality characteristics are verified by conducting confirmation experiments for both filament wound and hand layup pipes.

Optimal combinations of parameters are determined based on assumed weightage of 1:2:3:4 for crater wear, flank wear, machining force and surface roughness, respectively. The weightage of parameters was assumed on the basis of physical significance of each parameter during machining. Surface roughness plays an important role in many areas and is a factor of greater importance in the evaluation of machining accuracy [11], and hence, it is given maximum weightage. Machining force plays the next prominent role after surface roughness [19], and therefore, the next best weightage was assumed to it. Apart from surface roughness and machining force, tool wear also contributes significantly in determining the optimum machining characteristics. Mostly, flank wear is considered,

Table 4 Individual desirability and composite desirability

Test condition number	Speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Individual desirability(d_i)—filament wound pipes				Composite desirability (d_G)	Individual desirability(d_i)—Hand layup pipes				Composite desirability (d_G)
				Flank wear	Crater wear	R_a	F_m		Flank wear	Crater Wear	R_a	F_m	
1	100	0.05	0.5	1.000	0.000	1.000	0.820	0.000	0.758	0.750	0.954	0.750	0.827
2	100	0.1	1	0.889	0.333	0.006	0.539	0.093	0.909	0.000	0.065	0.000	0.000
3	100	0.2	2	0.540	0.667	0.070	0.404	0.223	0.606	0.750	0.480	0.750	0.601
4	150	0.05	0.5	0.857	0.333	0.733	0.880	0.738	0.939	0.750	0.891	0.745	0.839
5	150	0.1	1	0.698	0.500	0.267	0.601	0.440	0.000	0.825	0.000	0.813	0.000
6	150	0.2	2	0.206	0.833	0.244	0.504	0.332	0.697	0.825	0.729	0.813	0.755
7	200	0.05	1	0.587	0.667	0.209	0.666	0.409	0.909	1.000	0.511	1.000	0.750
8	200	0.1	2	0.222	0.833	0.000	0.702	0.000	0.909	0.875	0.511	0.875	0.711
9	200	0.2	0.5	0.159	0.833	0.233	0.964	0.375	0.758	0.900	0.455	0.900	0.662
10	100	0.05	2	0.873	0.333	0.256	0.810	0.474	0.697	0.875	0.791	0.868	0.801
11	100	0.1	0.5	0.921	0.167	0.698	0.895	0.689	0.848	0.450	0.497	0.438	0.527
12	100	0.2	1	0.683	0.500	0.547	0.921	0.662	0.848	0.625	0.211	0.625	0.430
13	150	0.05	1	0.810	0.333	0.110	0.633	0.310	0.697	0.575	0.983	0.563	0.736
14	150	0.1	2	0.556	0.667	0.773	0.538	0.640	0.970	0.875	0.937	0.875	0.918
15	150	0.2	0.5	0.508	0.667	0.395	0.686	0.517	1.000	1.000	1.000	1.000	1.000
16	200	0.05	2	0.413	0.667	0.471	0.000	0.000	0.758	1.000	0.858	0.988	0.886
17	200	0.1	0.5	0.524	0.667	0.866	1.000	0.797	0.606	0.750	0.084	0.750	0.299
18	200	0.2	1	0.000	1.000	0.047	0.722	0.000	0.758	0.900	0.718	0.888	0.791

Table 5 Factor effects for composite desirability (d_G) for filament wound pipes

Levels	Factors		
	V	*f*	*d*
1	0.356842	0.321910	0.519195
2	0.496021	0.442907	0.318999
3	0.263423	0.351468	0.278092
Optimum levels	V_2	f_2	d_1

since it largely affects the stability of the cutting wedge and consequently the dimensional tolerance of the machined work surface [31]. Hence, the weightage for flank wear is assumed as the third best, whilst the weightage for crater wear was assumed to be the least. The individual desirability values for flank wear, crater wear, machining force and surface roughness are calculated and presented in Table 3. Based on assumed weightage, the composite desirability values are also calculated and tabulated in Table 3. The best values of various parameters for the combined objective (combined objective with 10% to crater wear, 20% to flank wear, 30% to machining force and 40% to surface roughness) of minimised tool wear, machining force and surface roughness are identified and presented in Figs. 3 and 4 for filament wound and hand layup pipes, respectively. The optimal combinations of parameters for filament wound GFRP pipes for better values of tool wear, machining force and surface roughness are identified as $V_2f_2d_1$ and the optimal combinations of parameters for hand layup GFRP pipes for better values of tool wear, machining force and surface roughness are identified as $V_2f_1d_3$ as shown in Figs. 3 and 4, respectively. The contradictory behaviour of the two materials selected is due to the variation in the mechanical properties. Since filament wound pipes possess better strength compared to hand layup pipes, it performs better with higher feed rate. Similarly, the higher depth of cut is suggested for hand layup pipes, since the strength of the hand layup pipes is far less compared to that of the filament wound pipes.

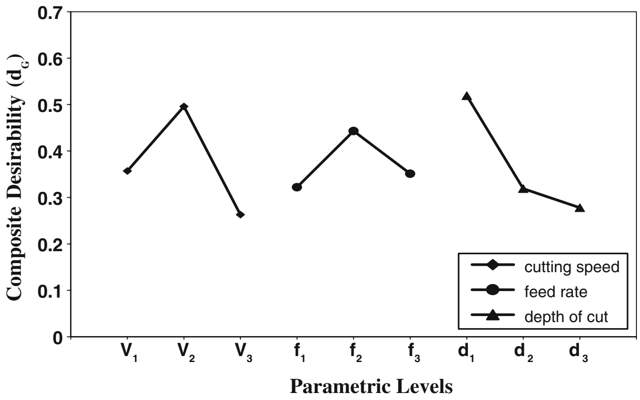

Fig. 3 Factor effects for composite desirability (d_G) for filament wound pipes

The purpose of the statistical ANOVA is to investigate which design parameter significantly affects the surface roughness, machining force and tool wear. Based on the ANOVA, the relative importance of the machining parameters with respect to surface roughness, machining force and tool wear was investigated to determine more accurately the optimum combination of machining parameters. The analysis is carried out for the level of significance of 5% (the level of confidence is 95%). Tables 7 and 8 show the results of ANOVA analysis for the machining outputs of filament wound and hand layup pipes, respectively. The third column in Tables 7 and 8 indicates the sum of square of each factor on the total variation, indicating their degree of influence on the results. The greater the sum of square value, the greater is the influence on a factor on the performance. From Table 7, the depth of cut was found to be the major factor affecting the performance of machining filament wound GFRP pipes, followed by cutting velocity and feed rate. From Table 8, the feed rate was found to be the major factor affecting the performance of machining hand layup GFRP pipes, followed by depth of cut and cutting velocity.

Table 6 Factor effects for composite desirability (d_G) for hand layup pipes

Levels	Factors		
	V	*f*	*d*
1	0.531168	0.806663	0.692355
2	0.708055	0.40919	0.451234
3	0.683309	0.70668	0.778944
Optimum levels	V_2	f_1	d_3

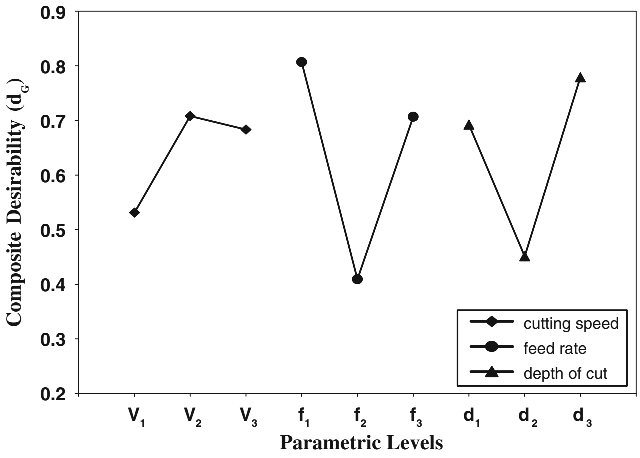

Fig. 4 Factor effects for composite desirability (d_G) for hand layup pipes

Table 7 ANOVA for composite desirability (d_G) for filament wound pipes

Factors	Degrees of freedom	Sum of square	Mean square	*F* test
V	2	0.164401	0.082201	1.057328
f	2	0.04775	0.023875	0.307099
d	2	0.199765	0.099883	1.284768
Error	11	0.85518	0.077744	1
Total	17	1.267095	0.074535	

3.2 Confirmation test

The purpose of the confirmation test is to validate conclusions drawn during the analysis phase. Once the optimum level of the process parameters is selected, the final step is to predict and verify the improvement of the performance characteristics using the optimum level of the process parameters. The confirmation experiment is conducted at the optimum test conditions to verify the quality characteristics for turning both filament wound and hand layup GFRP pipes, as recommended by the investigation. The summary of the results obtained from the confirmation tests are detailed below.

3.2.1 Filament wound pipes

A validation experiment is conducted for the combined objective with the obtained best levels of parameters. The values for flank wear, crater wear, machining force and surface roughness from validation experiment for filament wound pipes are 0.051 mm, 0.0045 mm, 38.54 N and 2.21 μm, respectively.

The percent improvement in flank wear, crater wear, machining force and surface roughness with the application of design of experiments is calculated from the validated result and the best values of responses from the Table 3 as:

$$\text{The \% improvement in flank wear} = [(0.059 - 0.051)/0.059] \times 100 = \mathbf{13.55\%}$$

$$\text{The \% improvement in crater wear} = [(0.005 - 0.004)/0.005] \times 100 = \mathbf{20.00\%}$$

$$\text{The \% improvement in machining force} = [(40.66 - 38.54)/40.66] \times 100 = \mathbf{5.21\%}$$

$$\text{The \% improvement in surface roughness} = [(2.35 - 2.21)/2.35] \times 100 = \mathbf{5.95\%}$$

3.2.2 Hand layup pipes

A validation experiment is conducted for the combined objective with the obtained best levels of parameters for hand layup pipes also. The values for flank wear, crater wear, machining force and surface roughness from validation experiment for hand layup pipes are 0.014 mm, 0.0065 mm, 7.10 N and 3.30 μm, respectively.

The percent improvement in flank wear, crater wear, machining force and surface roughness with the application of design of experiments is calculated from the validated result and the best values of responses from the Table 3 as:

$$\text{The \% improvement in flank wear} = [(0.015 - 0.014)/0.015] \times 100 = \mathbf{6.25\%}$$

$$\text{The \% improvement in crater wear} = [(0.0080 - 0.0065)/0.0080] \times 100 = \mathbf{18.75\%}$$

$$\text{The \% improvement in machining force} = [(7.50 - 7.10)/7.50] \times 100 = \mathbf{5.33\%}$$

$$\text{The \% improvement in surface roughness} = [(3.73 - 3.30)/3.73] \times 100 = \mathbf{11.53\%}$$

4 Conclusion

Turning experiments were conducted based on Taguchi technique for both filament wound and hand layup GFRP pipes using K_{20} grade cemented carbide cutting tool. The experimentally collected data were subjected to desirability function analysis for optimisation of machining parameters. From this analysis, the following conclusions are drawn for flank wear, crater wear, machining force and surface roughness.

- Desirability function in the Taguchi method for the optimisation of multi-response problems is a very useful tool for predicting surface roughness, machining force and tool wear in turning GFRP pipes.
- The application of desirability function analysis in DOE improves the flank wear, crater wear, machining force and surface roughness by 13.55%, 20.00%, 5.21% and 5.95%, respectively, for filament wound pipes.
- The application of desirability function analysis in DOE improves the flank wear, crater wear, machining force and surface roughness by 6.25%, 18.75%, 5.33% and 11.53%, respectively, for hand layup pipes.
- Depth of cut is the significant machining parameter followed by cutting velocity and feed rate for machining filament wound GFRP pipes, and feed rate is the significant machining parameter followed by depth of

Table 8 ANOVA for composite desirability (d_G) for hand layup pipes

Factors	Degrees of freedom	Sum of square	Mean square	*F* test
V	2	0.110097	0.055049	1.327168
f	2	0.512962	0.256481	1.482284
d	2	0.346062	0.173031	4.171615
Error	11	0.45626	0.041478	1
Total	17	1.425383	0.083846	

cut and cutting velocity for machining hand layup GFRP pipes.

- Moderate cutting velocity, lower feed rate and higher depth of cut are the ideal machining conditions for machining hand layup GFRP pipes and moderate cutting velocity, Moderate feed rate and lower depth of cut are the ideal machining conditions for machining filament wound GFRP pipes.

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