Multi-response parametric optimization in drilling of bamboo/Kevlar fiber reinforced sandwich composite

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Abstract. In the present work an attempt was made towards parametric optimization of drilling bamboo/Kevlar K29 fiber reinforced sandwich composite to minimize the delamination occurred during the drilling process and also to maximize the tensile strength of the drilled composite. The spindle speed and the feed rate of the drilling operation are taken as the input parameters. The influence of these parameters on delamination and tensile strength of the drilled composite studied and analysed using Taguchi GRA and ANOVA technique. The results show that both the response parameters i.e. delamination and tensile strength are more influenced by feed rate than spindle speed. The percentage contribution of feed rate and spindle speed on response parameters are 13.88% and 81.74% respectively.

Keywords. Bamboo, Kevlar, Taguchi GRA, ANOVA

1. Introduction
The soaring price, intimidation to the ecology, exhaustion of the natural reservoirs, carcinogenic nature, etc. of conventional and petroleum based fiber reinforced polymer composites, have forced the researchers to find alternative materials, which are naturally redeemable, for development and fabrication of polymer composites [1]. This leads to the development of biocomposites based on natural fibers. Apart from being renewable and eco-friendly nature, the production of natural fibers cost, on average, 60% less than that of commonly used synthetic fiber such as glass fiber [2]. Natural fibers also exhibit certain advantageous features over man-made fibers i.e., lower cost, lower density, comparable specific tensile properties, non-abrasive to the equipments, non-irritation to the skin, etc. Some of the popular natural fibers used for reinforcing polymer composites include bamboo, jute, sisal, cotton, coir, flax fibers, etc. Among these, bamboo fiber is regarded as an excellent candidate for the development of sustainable natural fiber based biocomposites due to its superior mechanical and thermal properties, structures, availability of different techniques of fiber extraction and chemical treatment [3-5]. In addition to this, it grows very rapidly at a rate of up to several centimeters per day [6] and thus increases its availability as the raw material.

Though, the natural fiber based biocomposites possess excellent properties and considered as the potential replacement for available synthetic fibers in polymer composites, they still suffer from lower modulus, lower strength and relatively poor moisture resistance compared to synthetic fibers [7].
of them have tensile and flexural strength lower than 100 MPa. Therefore, its application in high strength applications has been restricted. Recently, researchers have started to hybrid the natural biocomposites with synthetic fibers in order to improve its properties for advanced composite applications [8]. Incorporation or hybridization of high strength, moisture and corrosion resistant synthetic fibers such as glass, carbon, Kevlar fibers, etc. could enhance the composite properties. One of the most significant achievements of hybrid composite is the balance between the cost and performance of the composite, which is hard to obtain with a monolithic composite. The above mentioned advantage of hybrid composite is more pronounce with the proper selection of reinforcing fibers and processing techniques, which would allow to engineer the composite according to the require practical applications economically. Among the popular synthetic fibers, Kevlar (aramid) fiber exhibits very attractive and superior properties. It also possesses density comparable to that of bamboo and thus the specific strength of the composite will not be compromised. Moreover, to the extent of the literature review performed by the author, no researchers have reported the work regarding the hybridization of bamboo and Kevlar fibers till date. Therefore, the authors have opted to hybridize Kevlar with bamboo fiber for the present work.

In the recent years, composites based on natural fibers are used in fabricating parts of automobiles such as Side panels, Insulation components of car, Transport pallets, etc. [9]. These composite parts, even though, are separately fabricated using different fabrication techniques such as hand layup, pultrusion, filament winding, resin transfer moulding, etc., they are required to be assembled together in order to attain the final finished product. The assembly process requires creation of holes in these composite parts for riveting and fastening purpose [10-12]. Although both conventional and non-conventional drilling operations are available for hole creation, conventional method is still widely preferred due to its simplicity and cost effectiveness [13]. The conventional drilling in FRP composites imposed several damages such as delamination, burrs, swelling, splintering, surface roughness, fiber pull outs, etc. [14] due to its anisotropy and non-homogeneous nature such as diverse fibre and matrix properties, fibre orientation and relative volume of the matrix and the fibres. These drilling induced damages lead to the stress concentration, which drastically reduces the mechanical properties of the composite. About 60% of the parts in industries are rejected due to the bad quality of drilled holes [15]. Delamination is considered as one of the major threat in drilling of FRP composites. In the drilling operation, as the drill gradually progresses, the thickness of the uncut section of composite reduces and after certain time period, the thickness becomes critical. And thus the resisting force of the uncut laminate falls below the drill induced thrust force, therefore causing the separation of bottom laminate from the rest of the composite by breaking the inter-laminar bond. This separation of laminas is termed as delamination. The machining parameters such as spindle speed and feed rate play a vital role in controlling the degree of this damage. For this reason, the effect of these parameters is needed to be studied and analysed carefully so that, the induced damage is reduced to the minimum.

Different researchers carried out studies to improve the drilling of FRP composites. Palanikumar et al. studied the influence of spindle speed, feed rate and drill diameter on the thrust force, workpiece surface roughness and delamination occurred during the drilling process in glass fiber reinforced polymer (GFRP) composite [16,17]. Taguchi’s method and grey relational analysis was performed for this purpose. Mohan et al. also investigated delamination in drilling of GFRP composite and stated that cutting speed, feed rate and material thickness influenced it significantly [18]. Babu et al. employed Taguchi’s method and ANOVA technique to analyse the delamination and tensile strength in drilling operation of uni-directional hemp fiber reinforced composite [19]. Veerapuram et al., in another work, attempted to investigate the effect of cutting speed, feed rate and fiber treatment on delamination induced during drilling operation of jute fiber reinforced polymer composite [20]. Factorial design based experiments and GRA analysis were used for the study. Latha et al. employed fuzzy logic to study the effect of different cutting parameters on delamination induced during the drilling of GFRP and found that spindle speed and feed rate were the most influential machining parameters [21]. In another investigative work, Piquet et al. studied the effect of drill geometry on the induced damage during drilling of thin carbon/epoxy laminates [22]. Two types of drills i.e. helical and special geometry drills were used and concluded that, the uses of special type drill significantly reduces the damage in the drilled hole.
Taguchi method, a robust optimizing tool, was developed by Dr. Genichi Taguchi of Japan. It can be used for designing the experiment and examine how the process parameters influence the performance parameters [23]. Unlike the factorial design method, it doesn’t use all the possible combinations of process parameters. This helps in saving time and resources by collecting only the required data with minimum experimentations. Along with grey relational analysis (GRA), this method can be used for optimizing multi response machining operations. Apart from Taguchi method, analysis of variance (ANOVA) is used in determining the effect of various machining parameters on output parameters by conducting an F-test [24].

In this current study, the parametric optimization for drilling operation of bamboo/Kevlar fiber reinforced hybrid sandwich composite is performed using GRA method with Taguchi design to minimize the delamination and maximize the tensile strength of the fabricated composites.

2. Experimental Procedure

2.1. Composite fabrication and specimen preparation

Plain woven bamboo fiber mat and Kevlar K29 fabric of GSM 280±20 with bi-directional fiber orientation of 0°/90° are used as the reinforcement material for fabricating the composite. Epoxy resin (LAPOX B-11) and Triethylenetetramine (T.E.T.A.) are used as matrix material and hardener respectively. In order to remove the absorbed moisture, bamboo fiber was dried in a vacuum oven, so that efficient bonding between the fiber and matrix is achieved. Hand layup technique was followed for composite fabrication. The required number of laminas is stacked with bamboo laminas placed in between the Kevlar laminas and cured at room temperature for 24 hours. The fiber volume fraction were maintained at 0.4 i.e., \( V_f = 40\% \). ASTM D3039/D3039M–00\(^1\) was followed for preparing the composite sample for test.

2.2. Machining setup

The drilling operation of the fabricated composite specimens is performed on the conventional radial drilling machine under dry condition in room temperature. Standard twist drills made up of tungsten carbide with 6 mm diameter and 118° point angle are used. The drilling operations are performed at different cutting speeds and feed rates, which are specified in the following section in details.

2.3. Design of experiment

Taguchi’s L\(_9\) orthogonal array is used for designing the experiment, since it helps in reducing the required number of experiments for gathering the data drastically [25-27]. After thorough review, it was found that cutting speed and feed rate are the most influencing parameters in drilling of FRP composite. Therefore, these two factors are opted for analysing in this work. 3 levels for each parameters i.e. 3 different cutting speeds and feed rates are selected and listed in table 1. ANOVA analysis of the experimental data is conducted to determine the contribution of each input parameters to the output parameters i.e. delamination factor and tensile strength of drilled composite.

| Process Parameters | Low (1) | Medium (2) | High (3) |
|--------------------|---------|------------|----------|
| Cutting Speed (rpm) (A) | 1120    | 1800       | 2800     |
| Feed Rate (mm/rev) (B)   | 0.032   | 0.05       | 0.08     |

\(^1\) ASTM D3039/D3039M–00
2.4. Measurement of delamination factor and tensile strength

The toolmaker’s microscope with resolution of 1µm and magnification of 30X was used to measure the extent of damage induced around the drilled hole. Each trial was repeated 2 times and the average value of the result was taken. A schematic diagram of the drilled composite is illustrated in the figure 1.

The delamination induced during the drilling operation is expressed in terms of delamination factor and is calculated using the following equation (i).

$$F_d = \frac{D_{\text{max}}}{D}$$  \hspace{1cm} (i)

Where, $D_{\text{max}}$ is the maximum diameter of the induced damage around the periphery of the drilled hole and $D$ is the diameter of the drill.

**Table 2. Experimental results**

| Trial no. | Cutting speed (rpm) (A) | Feed rate (mm/rev) (B) | Delamination factor ($F_d$) | Tensile strength (MPa) |
|-----------|-------------------------|------------------------|----------------------------|-----------------------|
| 1         | 1120                    | 0.032                  | 2.10                       | 54.40                 |
| 2         | 1120                    | 0.05                   | 2.26                       | 52.01                 |
| 3         | 1120                    | 0.08                   | 3.30                       | 50.06                 |
| 4         | 1800                    | 0.032                  | 1.75                       | 55.61                 |
| 5         | 1800                    | 0.05                   | 1.90                       | 54.02                 |
| 6         | 1800                    | 0.08                   | 2.34                       | 50.88                 |
| 7         | 2800                    | 0.032                  | 1.20                       | 53.10                 |
| 8         | 2800                    | 0.05                   | 1.91                       | 49.75                 |
| 9         | 2800                    | 0.08                   | 2.15                       | 48.40                 |

The tensile strength of the drilled composite is measured using INSTRON 8801 machine at a strain rate of 1.5 mm/minute. The detail of the experimental lay out plan along with the average value of delamination factor and tensile strength, taken as the response characteristic, is presented in table 2.
3. Results and discussion

3.1. Multi-objective optimization using grey relational analysis

Taguchi design with grey relational analysis is a powerful method for optimizing multi-objective problems. Using this technique, the problem with multi-objective performance is converted to single objective and then, the required optimum parameter for obtaining the desired performance characteristic is determined.

In GRA, the first step is to normalize the measured experimental results, so that the data are distributed evenly into an acceptable range for further analysis. Different normalization methods are adopted according to the desire quality characteristics. Since, in the current study, two different aims on response characteristics are there i.e. smaller the better for delamination factor and larger the better for tensile strength, two different normalization methods are adopted as follows:

For delamination factor, the lower which is the better, normalization method is expressed as,

\[ y_i^*(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \]  

For tensile strength, the higher which is the better, normalization method is expressed as,

\[ y_i^*(k) = \frac{x_i^0(k) - \min x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \]

Where \( x_i^0(k) \), \( \max x_i^0(k) \) and \( \min x_i^0(k) \) are the measured results, the maximum value of measured results and minimum value of the measured results respectively. Also, \( i \) is the number of experiments and \( k \) is the quality characteristics. The normalized values of the performance characteristics are shown in Table 3.

| Trial no. | Normalized Value |
|-----------|------------------|
|           | F_d              | Tensile Strength |
| 1         | 0.571            | 0.832            |
| 2         | 0.495            | 0.501            |
| 3         | 0.000            | 0.230            |
| 4         | 0.738            | 1.000            |
| 5         | 0.667            | 0.780            |
| 6         | 0.457            | 0.344            |
| 7         | 1.000            | 0.652            |
| 8         | 0.662            | 0.187            |
| 9         | 0.548            | 0.000            |

After normalizing of the obtained results, the next step is to determine the grey relational coefficient using the following equation (iv).

\[ \xi_j(k) = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_{ij}(k) + \zeta \Delta_{\max}} \]  

Where, \( \Delta_{ij}(k) \) is the deviation sequence of the reference sequence \( y_j^*(k) \) and the comparability \( y_j^*(k) \), i.e., \( \Delta_{ij}(k) = |y_j^* - y_i^*| \). \( \Delta_{\min} \) and \( \Delta_{\max} \) are respectively the minimum and maximum values of \( \Delta_{ij}(k) \). \( \zeta \) is the distinguishing coefficient and is normally taken as 0.5. The function of defining this
The grey relational coefficient is to show the relational degree between $y_0^*(k)$ and $y_j^*(k)$. The grey relational coefficient is computed using the equation (iv) and is illustrated in Table 4.

### Table 4. Grey relational coefficient and grades

| Normalized Variance | Gey relational coefficient | Gey relational grade | Rank |
|---------------------|---------------------------|----------------------|------|
| $F_d$ | $Tensile$ | $F_d$ | $Tensile$ | $F_d$ | $Tensile$ | |
| 0.571 | 0.832 | 0.429 | 0.168 | 0.538 | 0.749 | 0.644 | 4 |
| 0.495 | 0.501 | 0.505 | 0.499 | 0.498 | 0.501 | 0.4995 | 5 |
| 0.000 | 0.230 | 1.000 | 0.77 | 0.333 | 0.394 | 0.364 | 9 |
| 0.738 | 1.000 | 0.262 | 0.000 | 0.656 | 1.000 | 0.828 | 1 |
| 0.667 | 0.780 | 0.333 | 0.22 | 0.600 | 0.694 | 0.647 | 3 |
| 0.457 | 0.344 | 0.543 | 0.656 | 0.479 | 0.433 | 0.456 | 7 |
| 1.000 | 0.652 | 0.000 | 0.348 | 1.000 | 0.590 | 0.795 | 2 |
| 0.662 | 0.187 | 0.338 | 0.813 | 0.597 | 0.381 | 0.489 | 6 |
| 0.548 | 0.000 | 0.452 | 1.000 | 0.525 | 0.333 | 0.429 | 8 |

The final step in GRA is to determine the grey relational grade and is the average of grey relational coefficient of both the response characteristics. The grey relational grade is calculated and listed in Table 4. The higher grey relational grade indicates more ideal quality characteristics. Therefore, from Table 4, it is obtained that, the optimum combination of process parameter is $A_2B_1$ i.e. cutting speed of 1800 rpm and feed rate of 0.032 mm/rev. The response table of the grey relational grade is presented in Table 5.

### Table 5. Response table for grey relational grade

| Parameters | Level 1 | Level 2 | Level 3 | Delta | Rank |
|------------|---------|---------|---------|-------|------|
| $Cutting$ | 0.5025 | 0.6437 | 0.5710 | 0.1412 | 2 |
| $Speed$ (A) | | | | | |
| $Feed$ | 0.7557 | 0.5452 | 0.4163 | 0.3394 | 1 |
| $Rate$ (B) | | | | | |

The same values in the response tables are plotted in figure 2. In the response table, delta signifies the difference between the highest and lowest average values of response for a particular level. And rank indicates the degree of influence of machining parameters on response. It can be observed from the response table and graph that, out of both the process parameters, feed rate is more influential on the response characteristics.
Delamination of the composite is mainly caused due to the thrust force induced during drilling. And the increase in feed rate increases the load which in turn increased the thrust force. Therefore, delamination increases with the increase in feed rate. On contrary, when the cutting speed increases, the induced thrust force decreases due to the softening of matrix material. The softening of the matrix is caused due to the increase in heat generation. But, from the observed result, it is found that when the speed exceeds 1800 rpm the grey grade decreases. This is because, when speed passes 1800 rpm, thrust force slightly increases. Similar result was reported by Palanikumar [16] in the drilling of GFRP composite. The increase in thrust causes nucleation of damage in the drilled hole and leads to increase in stress concentration. This stress concentration reduces the tensile strength of drilled composite and causes catastrophic break down of composite when load is applied. In addition to the creation of stress concentration in the hole, proper load transfer between the matrix and fiber is restricted due to increased delamination with the increase in feed rate.

3.2. ANOVA analysis

Using ANOVA, the machining parameters are statistically analyzed and determine the significance or contribution of each of them on response of the process. It also helps in predicting the experimental error occurred. Table 6 illustrates the ANOVA results of grey relation grades. From the obtained result it is revealed that feed rate is more influential factor followed by cutting speed. Also, figure 3 shows the percentage contribution of each parameter on the response characteristic.

Table 6 ANOVA table for GRA

| Source | DF | Sum of squares | Mean Square | F-value | P-value | Percentage contribution |
|--------|----|----------------|-------------|---------|---------|------------------------|
| Speed  | 2  | 0.029901       | 0.0149504   | 6.34    | 0.057   | 13.88%                 |
| Feed   | 2  | 0.176055       | 0.0880277   | 37.34   | 0.003   | 81.74%                 |
| Error  | 4  | 0.009431       | 0.0023577   | 37.34   | 0.003   | 4.38%                  |
| Total  | 8  | 0.215387       |             |         |         |                        |
3.3. Confirmation test

Using Taguchi GRA optimization, the levels of process parameters for which the near optimal or the array of global optimal values of responses dwelled are obtained. The final step is to predict and verify the quality characteristic through confirmation test. The predicted value of responses is calculated by using the equation (v).

\[
\sigma = \sigma_i + \sum_{i=1}^{n} (\sigma_m - \sigma_i)
\]  

(\text{v})

Where \(\sigma_i\) and \(\sigma_m\) are the total mean of grey relational grade and mean of the grey relational grade at the optimal level, and \(n\) is the number of machining parameters. Table 7 illustrates the comparison between the predicted and experimental values of response parameters.

Table 8 Confirmation Results

| Performance Characteristics | Experimental (A2B1) | Predicted (A2B1) | Error Percentage |
|-----------------------------|--------------------|------------------|-----------------|
| Delamination Factor         | 1.75               | 1.579            | 9.7%            |
| Tensile Strength (MPa)      | 55.61              | 55.847           | 0.43%           |

4. Conclusions

In the present experimental study, GRA based on Taguchi design and ANOVA technique were employed to determine and analyse the optimum level combination of process parameters to minimize the delamination damage and maximize the tensile strength of the drilled composite in the drilling operation of bamboo/Kevlar fiber reinforced hybrid sandwich epoxy composite. The following conclusions are summarized from the obtained results:

1. Using GRA, the multi-objective problem is converted into single objective problem and evaluated with grey relational grade.
2. The optimum combination of parameter level is A2B1 i.e. cutting speed of 1800 rpm and feed rate of 0.032 mm/rev.
3. From response table and ANOVA results, it is revealed that feed rate is more dominant than cutting speed in determining the quality of the response characteristics.

Therefore, an optimal cutting speed with low feed is recommended in the drilling of the developed material in order to minimize the delamination damage and maximize the tensile strength of the drilled composite.
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