Drilling of a bidirectional jute fibre and cork-reinforced polymer biosandwich structure: ANN and RSM approaches for modelling and optimization

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Abstract
The present study examined the effects of drilling parameters such as spindle speed \(N\), feed rate \(f\), diameter of the tools \(d\) and drill geometry such as twist drills (HSS-TiN) and brad and spur drills (BSD) used on delamination damage in a biosandwich structure consisting of an epoxy matrix reinforced with bidirectional jute fibres and cork (JFCE). Response surface methodology (RSM) and artificial neural networks (ANNs) were exploited to evaluate the influence and interaction of the cutting parameters on the delamination factor \(F_d\) at the output during drilling. In addition, several optimization methods, such as desirability-based RSM, the genetic algorithm (GA) and the fmincon function, were applied to validate the optimal combination of cutting parameters \(f, N\) and \(d\) in the structures studied in biosandwiches during this research. According to the experimental results, severe damage was indeed observed with the BSD tool \(F_d = 1.684\) compared to the HSS-TiN tool \(F_d = 1.555\) for the same cutting conditions. To obtain the minimum \(F_d\), the optimum conditions obtained by GA were respectively 1397.54 rev/min, 51.162 mm/min and 5.981 mm for HSS-TiN for \(f, N\) and \(d\).

Keywords Industrial fabrics/textiles · Sandwich structures · Delamination · Drilling/machining · RSM/ANN · Genetic algorithm optimisation

1 Introduction
Over the past twenty years, plant fibres have proven to be an attractive environmentally friendly alternative to glass fibres in organic matrix composites due to the growth potential of plant fibres in the industrial sector [1–3]. The use of natural fibres as a reinforcement for polymer matrix composites has aroused, in recent years, the interest of researchers and industrialists from an economic and ecological point of view [4, 5]. This use is justified, first, by the use of local resources, development of materials and taking into account the environmental impact technologies and the reduction of production costs while maintaining good performance compared to that of synthetic fibre (glass and carbon). On the other hand, this is due to the potential of natural fibres in terms of mechanical properties that can compete for certain types of plant fibres, with synthetic fibres commonly used in industry [6–8]. Natural fibres are initially biodegradable and are often considered neutral to CO₂ emissions into the atmosphere because their biodegradation produces only a quantity of carbon dioxide. Biocomposites are therefore easier to recycle. These are mainly used in many fields, such as construction, sports, and transport. Indeed, in order to better understand the behaviour of these biocomposites, in-depth scientific studies have been carried out by several researchers [9, 10]. Currently, there are a wide variety of plant fibres that are currently used as reinforcements for different matrices [11], such as sisal [12], jute [12, 13], Agave americana L. [14], flax [15, 16], Washingtonia filifera [17], Luffa Vine [18] and bamboo [19].
However, machining is also an important operation when preparing composite surfaces for bonding assembly for multi-material applications [20]. The machinability of composites mainly depends on the structure and intrinsic characteristics of the fibres and the mechanical properties between the fibres and the resin responsible for the creation of various defects during machining, especially delamination, cracking, uncut fibres and the tearing of fibres, which lead to rough surfaces [21–23]. In the case of biocomposites with biofibre reinforcement, the mechanical behaviour of the fibres must be taken into account since this behaviour is much more prominent than that of the matrix, and because of the influence, this behaviour will have on the final state of the machined part. Several research works have addressed machining during the drilling of composites with synthetic fibres of glass, aramid and carbon to study the mechanisms of interaction between the cutting tools and the material and identify the most influential machining parameters in relation to the behaviour of the fibres and thus choose the most suitable process [24–31]. However, the literature contains only a limited number of works dealing with machining biocomposites [32–55] and comparative studies between biocomposites and composites with glass fibres [56]. The phenomenon most studied by researchers is delamination during drilling. Indeed, several theories and techniques exist in the literature to determine the delamination factor [21, 31, 57, 58]. Indeed, standard high-speed steel twist drills (HSS) [39, 46, 47, 50, 54, 55, 59] or tungsten carbide (WC) [47] is the most common tools used. The drill point angle is usually chosen to be 118° with tool diameters ranging from 3 to 14 mm. There are also other types of tools tested for drilling biocomposites, such as a tungsten carbide brad drill [56] and an HSS drill with two cutting edges [55].

Aravindh and Umanath used Taguchi’s method in the case of drilling NFC biocomposites (jute, sisal and bamboo fibres) to determine the optimal drilling conditions to minimise delamination. The authors estimated the contributions of different elements under optimal drilling conditions, including drill diameter (88.19%), feed rate (7.64%) and spindle speed (2.62%). Drilling tests conducted by Mercy et al. [60] on epoxy reinforced with pineapple fibre biocomposites at different orientations were performed under different machining conditions using an L27 orthogonal array from Taguchi. The results showed that a lower feed rate, higher speed and smaller drilling diameter minimise the pushing force. Nagamadhu et al. [61] conducted a study of delamination during drilling to different drill diameters of a composite sandwich reinforced vinyl ester with unidirectional sial fibres using various cutting parameters. The authors used the Taguchi method L9 to optimise the input parameters to minimise delamination. The researchers concluded that the optimal parameters of drill diameter, spindle speed and feed rate given by ANOVA were 6 mm, 3000 rpm and 50 mm/min, respectively. Machado et al. [62] proposed a new method for evaluating Fd (delamination factor). This technique is based on digital radiography image acquisition of the damaged area during drilling. In a recent work, Belaadi et al. [21] conducted an interesting investigation aimed at the effect of drilling parameters such as spindle speed, feed rate and drilling diameters on short jute fibre/polyester biocomposites to evaluate the effect of the delamination factor Fd. In other recent work, Belaadi et al. [22] developed an ANN model to assess the interactions of cutting parameters to analyse delamination. In their tests, hole exit damage was measured using a high-resolution scanner and then processed by ImageJ to calculate the delamination factor. The results revealed that delamination is sensitive to each cutting parameter.

Therefore, the novelty of this study is to focus on the influence of drilling parameters on the delamination factor of biosandwich structures using cork agglomerated cores with epoxy reinforced with woven jute fibres (WF). Two tools with different diameters were chosen: conventional HSS-TiN (high-speed steel coated with titanium nitride) drills and wood drills (brad and spur), to estimate the influence and simultaneous interaction of the input parameters on the factor Fd. Indeed, response surface methodology (RSM) and artificial neural networks (ANNs) were utilised to estimate the influence and interaction of cutting parameters on output delamination in drilling. Finally, optimization functions such as desirability based on the RSM method, function fincon and genetic algorithm (GA) were employed to confirm the optimal combination of optimal cutting parameters (f, N and d) in the biosandwich structures studied in this work.

2 Materials and methods

2.1 Biosandwich manufacturing

In this study, the reinforcement is composed of a bidirectional jute fibre (Fig. 1) having a surface mass of 160 g/m² (28 × 23 yarns/100 mm) and an epoxy resin classified as MEDAPOXY STR, furnished by the GRANITEX company (Algeria), which has a density of 1.110 kg/m³. The average tensile mechanical properties of epoxy resin used in this paper have been described by Belaadi et al. and Cherief et al. [12, 22] in previous work (tensile strength of 43.13 MPa, elongation of 4.03% and Young’s modulus of 2.47 GPa). Additionally, materials were used as agglomerate cores in the manufacturing of biosandwich samples as cork, with a thickness of 15 mm and a nominal density of 280 kg/m³. The jute fabric, agglomerate cork and epoxy resin were procured from local sources. The preparation of the biosandwich samples (jute/cork/epoxy) was performed by a contact moulding process by hand and then cut to dimensions of 300 mm × 300 mm. The obtained sandwich structure was a rectangular sheet 300 mm long, 300 mm
Biosandwich (jute/Cork/epoxy)

Jute fabric (160 g/m²)

Epoxy resin

Cork

Biosandwich

Jute fabric (160 g/m²) and cork

Spindle speed (N)
Feed rate (f)
HSS-TiN and Brad & Spur drills (BSD)

Cutting parameters

Drilling behaviour

Numerical image processing operation

**Table 1** Process parameters available in open literature for drilling of jute fibre-reinforced polymer composites

| Matrix       | Fibre                          | Fibre content (% w/w) | Cutting parameters | Tool material | Drill diameter (mm) | Feed rate (mm/rev) | Spindle speed (N, rpm) | References |
|--------------|--------------------------------|-----------------------|--------------------|---------------|---------------------|--------------------|----------------------|------------|
| Epoxy        | Unidirectional jute            | -                     | HSS twist drills    | 6, 8, 10      | 50, 150, 250         | 1000, 2000, 3000    | [49]                 |
| Polyester    | Treated and untreated jute     | 30                    | HSS twist drill     | 6             | 0.03, 0.06, 0.09, 0.12| 36, 72, 108, 216    | [50]                 |
| Epoxy        | Treated and untreated jute     | 30                    | HSS twist drill     | 6             | 0.03, 0.06, 0.09, 0.12| 36, 72, 108, 216    | [51]                 |
| Polypropylene (PP) | Jute fabric | 30, 40, 50 | Twist drills, parabolic drills | Epoxy twist drill | 8 | 0.05, 0.12, 0.19 | 900, 1800, 2800 | [52] |
| Epoxy        | Jute fabric                    | 43                    | HSS twist drill     | 8             | 0.05, 0.10, 0.15    | 750, 1250, 1750     | [67]                 |
| Polyester    | Glass-sisal-jute               | -                     | Brad and spur, coated carbide | 6, 9, 12 | 0.04, 0.06, 0.08 | 1000, 2000, 3000 | [68] |
| Vinyl-ester  | Untreated                     | -                     | Twist drills, 60°, 90°, 120°, 150° | 10 | 0.1, 0.2, 0.3, 0.4 | 500, 1000, 1500, 2000 | [69] |
| Vinyl-ester  | Treated (NaOH)                | -                     | Twist drills, 60°, 90°, 120°, 150° | 10 | 0.1, 0.2, 0.3, 0.4 | 500, 1000, 1500, 2000 | [70] |
| Epoxy        | Glass-flax-jute               | -                     | Drill bit carbide   | 6, 8, 10      | 0.1, 0.2, 0.3       | 600, 1200, 1800     | [71]                 |
| Polyester    | Short jute fibre 5, 10 and 15 mm | 40               | Brad & Spur drills Twist drills | 5, 7, 10 | 50, 108, 190 | 355, 710, 1400 | [21] |
| Epoxy        | Jute fabric (210 g/m²)        | 40                    | Brad & Spur drills Twist drills (HSS) | 5, 7, 10 | 50, 108, 190 | 355, 710, 1400 | [22] |
| Polyester    | Jute fabric and steel fibres  | -                     | Twist drills (HSS-TiN) | 8,10,12 | 0.1, 0.2, 0.3 | 500, 1250, 2000 | [72] |
| Polypropylene | Unidirectional Jute          | 30                    | HSS, Co-HSS         | 2, 3, 4       | 0.1, 0.2, 0.3       | 600, 1260, 2700     | [73] |
| Epoxy        | Jute and flax fabric          | -                     | HSS, HSS-TiN, WC    | 4             | 0.01, 0.015, 0.020  | 2500, 5000, 7500    | [74] |
| Epoxy        | Jute fabric (160 g/m²) and cork | 30               | Brad and spur drills and twist drills (HSS-TiN) | 5, 7, 10 | 50, 108, 190 | 355, 710, 1400 | This work |

**Fig. 1** Schematic arrangement of experimental setup of the biosandwich structure
wide and approximately 20 ± 0.8 mm thick and was made up of five layers. In addition, the biosandwich had a 30% fibre content by weight. The EBJWC assembly was cured and held in the mould at atmospheric standard pressure (1 bar) until curing was complete for 24 hours at an ambient temperature of 25 °C. The plates were kept in open air for 15 to 20 days to ensure complete polymerisation of the resin. Finally, they were then post-cured at 50 °C for 8 hours in an oven. Following fabrication, the samples for drilling experiments were cut to the following dimensions: 290 × 100 × 20 mm³. A diamond saw was used to cut the specimens, which were lubricated with water to avoid heating caused by the cutting process. The specimens were then air-dried at room temperature (25 °C) for 20 days.

### 2.2 Drilling experimental procedure

The drilling tests were performed with a MOMAC universal drill using a 1400 rev/min spindle and a feed rate of 4.6 to 1040 mm/rev [21, 22], and all drilling was performed on this machine. To reduce the bending of the parts (and thus not include the influence of this structural parameter in this study) while drilling the hole, a solid steel support was used underneath the parts in the sandwich to avoid amplifying the size of the defect at the exit of the hole. To perform the drilling tests, we need a workpiece (EBJWC) size geometry of 290 × 100 × 20 mm³ and a device for fixing the part is shown in Fig. 1. Brad and spur and twist HSS-TiN drills of different diameters (5 mm, 7 mm and 10 mm) were used in this study, whose shape and tool geometry are presented in Fig. 1. It is important to note that hole drilling in this study is performed in one phase (step). To obtain high-quality holes and prevent the drilling tool wear factor, the drill bit was replaced with a new bit after four to five operations. Drilling was done dry without coolant. In addition, other settings were also

| n° | Factors     | Notation | Unite | Levels         |
|----|-------------|----------|-------|----------------|
| 1  | Spindle speed | N        | rev/min | 355 710 1400   |
| 2  | Feed rate   | f        | mm/min | 50 108 190     |
| 3  | Drill diameter | d     | mm     | 5 7 10         |

![Fig. 2](image_url) Typical holes drilled on jute/cork/epoxy biosandwich plate a entrance, b cross section and c exit delamination for three test (#4, #13 and #22)
employed, such as 355, 710 and 1400 rpm spindle speeds and three feed rates that we chose (50, 108 and 190 mm/min). The selection of machining parameters was based on a literature review, which is presented in Table 1.

Next, drilled samples were digitally scanned with a high-resolution scanner at up to 2400 × 4800 dpi (48 bit internal colour depth) to obtain a high-quality image. Image digital results are imported into and processed in ImageJ (free software v1.47, published by the National Institute of Health, USA [50, 51, 63]) for damage area measurement of the drilled hole Fd, and the threshold factor was fitted to indicate delamination surrounding the hole. Delamination is a main damage defect in the drilling of laminated composites. The procedure used to acquire different damaged areas in a drilled hole is

| Test number | Input variables | Output variables |
|-------------|-----------------|------------------|
|             | f (mm/min) | N (rev/min) | d (mm) | $F_{d_{HSS-TiN}}$ | $F_{d_{BSD}}$ |
| 1           | 50       | 355   | 5   | 1.084 | 1.078 |
| 2           | 108      | 355   | 5   | 1.176 | 1.152 |
| 3           | 190      | 355   | 5   | 1.312 | 1.309 |
| 4           | 50       | 710   | 5   | 1.025 | 1.107 |
| 5           | 108      | 710   | 5   | 1.218 | 1.173 |
| 6           | 190      | 710   | 5   | 1.334 | 1.333 |
| 7           | 50       | 1400  | 5   | 1.045 | 1.092 |
| 8           | 108      | 1400  | 5   | 1.201 | 1.163 |
| 9           | 190      | 1400  | 5   | 1.355 | 1.328 |
| 10          | 50       | 355   | 7   | 1.127 | 1.086 |
| 11          | 108      | 355   | 7   | 1.181 | 1.168 |
| 12          | 190      | 355   | 7   | 1.321 | 1.350 |
| 13          | 50       | 710   | 7   | 1.117 | 1.109 |
| 14          | 108      | 710   | 7   | 1.217 | 1.193 |
| 15          | 190      | 710   | 7   | 1.320 | 1.377 |
| 16          | 50       | 1400  | 7   | 1.119 | 1.100 |
| 17          | 108      | 1400  | 7   | 1.246 | 1.188 |
| 18          | 190      | 1400  | 7   | 1.302 | 1.378 |
| 19          | 50       | 355   | 10  | 1.136 | 1.161 |
| 20          | 108      | 355   | 10  | 1.206 | 1.270 |
| 21          | 190      | 355   | 10  | 1.464 | 1.488 |
| 22          | 50       | 710   | 10  | 1.298 | 1.188 |
| 23          | 108      | 710   | 10  | 1.279 | 1.298 |
| 24          | 190      | 710   | 10  | 1.481 | 1.520 |
| 25          | 50       | 1400  | 10  | 1.171 | 1.188 |
| 26          | 108      | 1400  | 10  | 1.275 | 1.302 |
| 27          | 190      | 1400  | 10  | 1.555 | 1.529 |

Table 3 Experimental results for delamination factor of the drilled holes at the exit

| RSM response | Drill geometry | HSS-TiN |
|--------------|----------------|---------|
| $F_d$        | $1.252-0.579\times10^{-3}\times f+0.106\times10^{-3}\times N-0.070\times d+1.016\times10^{-7}\times f\times N+1.504\times10^{-4}\times f\times d+4.110\times10^{-6}\times N\times d+5.725\times10^{-6}\times f^2-7.276\times10^{-8}\times N^2+0.005\times d^2$ |
| BSD          | $0.442+2.258\times10^{-3}\times f-0.709\times10^{-3}\times N+0.225\times d+4.631\times10^{-7}\times f\times N-1.100\times10^{-5}\times f\times d+2.425\times10^{-3}\times N\times d-5.286\times10^{-7}\times f^2+2.565\times10^{-7}\times N^2-0.014\times d^2$ |

Table 4 Mathematical models for delamination factor for drilling of jute fabric-cork/epoxy biosandwich structure obtained with RSM method
shown in Fig. 1. The damage (delamination) was estimated in terms of the delamination factor \((F_d)\). The delamination factor at exit was determined by the following equation:

\[
F_d = \frac{D_{\text{max}}}{D}
\]  

(1)

where \(D\) is the nominal diameter of the drilled hole, \(D_{\text{max}}\) is the maximum diameter of delamination and \(F_d\) is a conventional delamination factor.

An orthogonal array \((L_{27})\) of central composite design (CCD) was adopted as the experimental design in this study. It was selected to decrease the number of experiments. Therefore, the experimental cost and time were minimised. For all three factors, namely, the drill diameter \((d)\), spindle speed \((N)\) and feed rate \((f)\), three levels in each factor were envisaged in this study (Table 2).

### 3 Results and discussion

#### 3.1 Influence of the drilling parameters on the delamination factor

Figure 2 illustrates the condition of the holes drilled at the entrance and the exit (#4, #13 and #22) with feed rates of 50, 108 and 190 mm/min and a spindle speed of 355 rpm. Digital images of the machined biosandwich plates were taken with a resolution of 4800 pixels using a professional scanner. Two concentric circles were drawn using an image processing

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**Table 5** ANOVA for the response surface quadratic model for delamination factor

| Source | DF | SS   | MS    | F-value | P-value | Cont. % | Remarks                  |
|--------|----|------|-------|---------|---------|---------|--------------------------|
| (a) ANOVA for delamination factor of HSS-TiN |    |      |       |         |         |         |                          |
| Model  | 9  | 0.47 | 0.052 | 13.34   | < 0.0001|         | Significant               |
| \(f\)  | 1  | 0.35 | 0.35  | 89.92   | < 0.0001| 66.04   | Significant               |
| \(N\)  | 1  | 2.338E-003 | 2.338E-003 | 0.60 | 0.4483 | 0.30 |                          |
| \(d\)  | 1  | 0.083 | 0.083 | 21.47   | 0.0002  | 10.54  |                          |
| \(f \times N\) | 1  | 1.732E-004 | 1.732E-004 | 0.045 | 0.8352 | 0.02 |                          |
| \(f \times d\) | 1  | 8.508E-003 | 8.508E-003 | 2.19 | 0.1570 | 1.08 |                          |
| \(N \times d\) | 1  | 3.626E-004 | 3.626E-004 | 0.93 | 0.7635 | 0.05 |                          |
| \(f \times f\) | 1  | 4.405E-003 | 4.405E-003 | 1.14 | 0.3016 | 0.56 |                          |
| \(N \times N\) | 1  | 1.843E-003 | 1.843E-003 | 0.47 | 0.5000 | 0.23 |                          |
| \(d \times d\) | 1  | 5.568E-003 | 5.568E-003 | 1.43 | 0.2474 | 0.71 |                          |
| Error  | 17 | 0.066 | 3.880E-003 |       |         |       |                          |
| Total  | 26 | 0.53  |       |         |         |       |                          |

\(SD = 0.062\)

\(Mean = 1.245\)

\(Coefficient of variation = 4.999\%\)

\(Predicted residual error of sum of squares (PRESS) = 0.156\)

\(R^2 = 87.59\%\)

\(R^2 adjusted = 81.02\%\)

\(R^2 predicted = 70.51\%\)

\(Adequate precision = 11.681\)

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**Table 5** ANOVA for the response surface quadratic model for delamination factor

| Source | DF | SS   | MS    | F-value | P-value | Cont. % | Remarks                  |
|--------|----|------|-------|---------|---------|---------|--------------------------|
| (b) ANOVA for delamination factor of BSD |    |      |       |         |         |         |                          |
| Model  | 9  | 0.7036 | 0.0782 | 15.8494 | 0.0000  |         | Significant               |
| \(f\)  | 1  | 0.5200 | 0.5200 | 105.4197 | 0.0000  | 66.03  | Significant               |
| \(N\)  | 1  | 0.0024 | 0.0024 | 0.4799  | 0.4978  | 0.30 |                          |
| \(d\)  | 1  | 0.1152 | 0.1152 | 23.3487 | 0.0002  | 14.63  |                          |
| \(f \times N\) | 1  | 0.0036 | 0.0036 | 0.7290  | 0.4051  | 0.46 |                          |
| \(f \times d\) | 1  | 0.0000 | 0.0000 | 0.0092  | 0.9246  | 0.00 |                          |
| \(N \times d\) | 1  | 0.0126 | 0.0126 | 2.5587  | 0.1281  | 1.60 |                          |
| \(f \times f\) | 1  | 0.0000 | 0.0000 | 0.0076  | 0.9315  | 0.00 |                          |
| \(N \times N\) | 1  | 0.0229 | 0.0229 | 4.6458  | 0.0458  | 2.91 |                          |
| \(d \times d\) | 1  | 0.0430 | 0.0430 | 8.7090  | 0.0089  | 5.46 |                          |
| Error  | 17 | 0.0839 | 0.0049 |         |         |       |                          |
| Total  | 26 | 0.7875 |       |         |         |       |                          |

\(SD = 0.070\)

\(Mean = 1.343\)

\(Coefficient of variation = 5.23\%\)

\(Predicted residual error of sum of squares (PRESS) = 0.208\)

\(R^2 = 89.35\%\)

\(R^2 adjusted = 83.71\%\)

\(R^2 predicted = 73.49\%\)

\(Adequate precision = 14.101\)
The damage caused by drilling holes in the manufacture of biosandwiches is part of the delamination factor. This is conditioned by the choice of cutting parameters as well as by the fibre fabric used. Delamination is a fundamental concern for the choice of cutting parameters during the design process. Determination of the delamination factor $F_d$ of biosandwich structures with agglomerated cork-core with epoxy skins reinforced with woven jute (EBJWC) for two drills using HSS-TiN and BSD is related to many factors such as feed rate, cutting speed and tool diameter.

### 3.2 Response surface methodology and ANOVA for delamination factor

The experimental results were processed using a response surface analysis and to determine the relationship between

![Graphs showing predicted vs. actual values and normal probability distribution of F_d residuals for different drills used in this work.](image-url)
the delamination and different cutting parameters for HSS-TiN and BSD. Table 3 shows the output parameters represented by the delamination factor for the two drills used in the present study, $F_d$(HSS-TiN) and $F_d$(BSD), performed under different machining conditions. These results were obtained according to the optimal design, which consists of analysing the influence of numerical factors on the responses with three levels and three input parameters ($f$, $N$ and $d$). Indeed, response surface methodology (RSM) is a mathematical and statistical method that is generally used in applied science and analytical problems such as the mechanics and machining of materials [64]. In addition, this technique represents an empirical modelling approach with the objective of finding the relationship between the input and output parameters, that is, delamination $F_d$, by changing the different cutting parameters during the drilling of biosandwiches. The mathematical equations of the regression are presented in Tables 4, 5 for the different delamination factors obtained by the Design-Expert.
software, which recommended quadratic models. Quadratic regression models are second-order mathematical models based on the RSM. Figure 3a and b highlight the relationship of predicted and experimental results for biosandwich structure delamination of HSS-TiN and BSD drills. Thus, the results obtained show satisfactory agreement of the regression model since the predicted values are statistically identical to the experimental values with a confidence level of 95%. The normal probability curves of the delamination residues $F_d$ are shown in Fig. 3c and d; the straight lines reveal a good distribution of errors. The synthesis of the relevance of the results reveals that the quadratic model is statistically significant for the analysis of delamination. Table 4 shows the results of the quadratic ANOVA model. The $R^2$ coefficient and the adjusted $R^2$ coefficient corresponding to the delamination are 87.59% and 81.02% for HSS-TiN and 89.35% and 83.71% for BSD,
Fig. 6 3D surface plots of delamination factor versus $f$, $N$ and $d$ of biosandwiches structures.
respectively. It is therefore obvious that this regression model offers a perfect match between the responses and the independent factors. The model is statistically significant because the p value corresponding to the model is less than 0.05. Additionally, factors \( f \) and \( d \) have significant effects on delamination. Due to the larger \( F_d \) value, it appears that the feed rate \( f \) and the diameter \( d \) are the most significant parameters for the delamination of HSS-TiN and BSD composites compared to \( N \). The rest of the terms in the model are considered insignificant. Therefore, it appears that the feed rate is the main parameter that affects the delamination factor, followed by the diameter and the cutting speed \( (N) \). In addition, the contribution of the factor \( f \) is the most important (66.04% and 66.03%) for HSS-TiN and BSD. The cutting speed has a less significant influence on delamination than the diameter on delamination.

### 3.3 3D surface plots for the delamination factor

Figures 4 and 5 describe a mapping in the form of the response surfaces provided for the delamination at the exit of the biosandwiches machined by the HSS-TiN and BSD drills as a function of the feed rate \( (f) \) and the cutting speed \( (N) \) and of the diameter \( (d) \). For the HSS-TiN tool, the delamination does not exceed 1.10 with a feed rate between 50 and 60 mm/min and a diameter of 5 to 7 mm, but further, the delamination exceeds 1.48 when the spindle speed is between 178 and 190 mm/min and a diameter of 9.4 to 10 mm (Fig. 4a). For the BSD tool, we also notice that the delamination does not exceed 1.09 for feed rates between 50 and 70 mm/min and a diameter of 5 to 5.5 mm, but it exceeds 1.62 when the cutting speed is between 185 and 190 mm/min and a diameter of 7.8 to 10 mm (Fig. 5a). Figures 4b and 5b show how the feed rate and spindle speed significantly affect delamination for the HSS-TiN and BSD drills. It can be seen that the delamination increases significantly with increasing feed rate and very slightly with increasing spindle speed. For HSS-TiN and BSD, the delamination is less than 1.10 when the feed rate is between 50 and 64 mm/min and the cutting speed is between 355 and 1400 rpm and is 1.09 for BSD when the feed rate is between 50 and 75 mm/min and that \( N \) is between 562 and 1400 rev/min. The delamination also seems to rise above 1.32

### Table 6

| Model          | Network structure | Percentage | Samples | RMSE          | R value        |
|----------------|-------------------|------------|---------|---------------|----------------|
| \( F_d(\text{HSS-TiN}) \) | 3-10-1         | Training 85          | 22        | 1.5537E-4    | 9.95854E-4    |
|                |                   | Validation 5         | 1         | 7.09654E-5   | 0.000000E-0   |
|                |                   | Testing 15           | 4         | 3.34586E-4   | 9.99250E-4    |
| \( F_d(\text{BSD}) \)  | 3-12-1         | Training 70          | 19        | 4.89445E-3   | 9.33291E-1    |
|                |                   | Validation 4         | 4         | 2.14720E-2   | 8.00842E-1    |
|                |                   | Testing 4            | 4         | 4.26253E-3   | 9.09048E-1    |
for HSS-TiN when the feed rate is between 182 and 190 mm/min and \( N \) is between 510 and 1400 rpm and equals 1.43 for BSD when the feed rate is between 174 and 190 mm/min and the spindle speed is between 355 and 1400 rpm. This corresponds perfectly to the results obtained in the work of Belaadi et al. [21, 22] in the case of epoxy/jute fabric biocomposites.
for the same cutting conditions. The effect of drill bit diameter and cutting speed ($N$) on delamination is shown in Figs. 4c and 5c. From this figure, it appears that the delamination increases as the diameter increases and increases slightly with the increase of $N$. The delamination is less than 1.32 and 1.47, when the diameter of the tool ($d$) and cutting speed are between 5 and 5.8 mm and 355 and 484 rpm for the HSS-TiN tool and 5 and 5.7 mm and 355 and 1400 rpm for the BSD drill, respectively. In addition, it is also observed that $F_d$ seems to exceed 1.52 and 1.62 when $d$ and $N$ are between 9.8-10 mm and 790-1400 rpm for HSS-TiN and 7.8-10 mm and 1295-1400 rpm for BSD, respectively. Figure 6 presents the evolution of the delamination factor as a function of cutting parameters such as the feed rate ($f$), spindle speed ($N$) and diameter ($d$). The delamination factor increases with increasing feed rate and drill diameter, as shown in Fig. 6a. The influence of these two cutting conditions ($f$ and $d$) is also considerable; this is mainly due to the forces produced and the amount of material removed during machining. Figure 6b illustrates the effect of drill diameter and spindle speed on $F_d$ for the two drills comprising HSS-TiN and BSD for a constant feed rate. The diameter of the drill has a great influence on the spindle speed, as clearly shown in Fig. 6b for the first drill (HSS-TiN). In the event that the diameter of the drill bit is kept constant (Fig. 6c), the factor $F_d$ increases with the increasing effect of the feed rate. On the other hand, by increasing the spindle speed, the delamination factor decreases. Generally, it emerges from Fig. 6 that the HSS-TiN drill ($F_d$ = 1.02 to 1.55) produces lower $F_d$ values than the BSD drill ($F_d$ = 1.11 to 1.68).

### 3.4 Prediction of delamination factor by ANN model

The data were integrated into the network model by the input layer and the response by the output layer. A multilayer perceptron consisting of an input layer, a hidden layer and an output layer was used for the prediction of the delamination factor. The architecture design of the ANN network was designed using the MATLAB Neural Network Toolbox.
Network Toolbox. Modelling by neural networks constitutes a powerful approach, making it possible to reproduce the behaviour of any nonlinear process of any kind [65]. For HSS-TiN and BSD drills, three neurons in the input layer, the hidden layers contain ten and twelve neurons, respectively, and one neuron for the output layer (Fig. 7). Determining the number of neurons in the hidden layers relies on reducing the error as the number of hidden nodes increases [66]. Table 6 shows the tested ANN architectures and MSE and R values for training, validation and testing of Fd data for the HSS-TiN and BSD drill tools. These neurons are linked together by means of weight weights. In Figure 8a–f, neural network prediction of Fd delamination and experimental test results for HSS-TiN and BSD tools, respectively, are compared for the training, testing and validation data sets. It emerges from Figs. 8 and 9 that the ANN prediction corresponds perfectly to the experimental results. The ANN models thus developed for HSS-TiN and BSD (Table 7) have the ability to interpret the data well and can serve as an efficient prediction tool for the delamination factor. In addition, the results show that the model is an efficient and applicable way to measure the delamination factor of biosandwiches made from jute fabric.

3.5 Comparison of RSM and ANN models

A comparison of the results predicted by the ANN and RSM models with those obtained experimentally are presented in Fig. 10. It was found that the two models satisfactorily describe the results obtained experimentally. The maximum absolute percentage error in the prediction of the delamination factors of the HSS-TiN and BSD tools by the ANN model is 4.16% and 6.28%, respectively, while in the RSM model, this percentage is 6.93% and 7.78% (Fig. 9). Thus, the ANN model provides a more accurate prediction than the RSM model. To the extent that these error rates are low, we can say that the optimization process is appropriate and that the model provides response prediction with high accuracy.

3.6 Optimisation of responses

Figures 12 and 13 illustrate the distribution of the ramp function and the mapping of the desirability contour for the two types of drill material as well as their combination in Fig. 12c. The main objective of the optimization is to determine the cutting parameters as well as the minimization of the delamination factors. The cutting parameters used in the optimization process are shown in Table 8, and the optimised values of the

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Table 7 Mathematical models for Fd for drilling of jute fabric-cork/epoxy biosandwich structure obtained with ANN method

| ANN response | Drill geometry |
|--------------|----------------|
| **HSS-TiN**  |                |
| Fd           | 1.1311×1.0657×H1×0.391×H2×0.701×H3×0.167×H4×0.1666×H5×0.0713×H6×0.0514×H7×0.0852×H8×0.0594×H9×0.0596×H10 |
| H1 = tanh(0.5 × (−0.0014 × f + 0.0028 × N + 0.4176 × d−5.7214)) |
| H2 = tanh(0.5 × (−0.0058 × f−0.0001 × N + 0.1945 × d−2.0769)) |
| H3 = tanh(0.5 × (0.0307 × f−0.0011 × N−0.5380 × d + 0.0155)) |
| H4 = tanh(0.5 × (−0.0115 × f + 0.0011 × N−0.5036 × d + 5.5330)) |
| H5 = tanh(0.5 × (−0.0160 × f + 0.0010 × N + 0.15627 × d + 0.3691)) |
| H6 = tanh(0.5 × (−0.1277 × f−0.0018 × N + 0.1578 × d + 4.2872)) |
| H7 = tanh(0.5 × (−0.0205 × f + 0.0026 × N−0.7482 × d + 7.9491)) |
| H8 = tanh(0.5 × (0.0088 × f−0.0023 × N+ 0.2148 × d + 0.4729)) |
| H9 = tanh(0.5 × (0.0145 × f + 0.0005 × N + 0.6481 × d−4.9054)) |
| H10 = tanh(0.5 × (0.0002 × f + 0.0003 × N + 0.4914 × d−4.5155)) |

| **BSD**       |                |
| Fd           | 1.3203−1.630×H1+1.4059×H2+0.4465×H3+0.9034×H4+0.0229×H5−0.8512×H6+0.0710×H7−0.6178×H8+0.20575×H9+0.6614×H10+0.9535×H11+0.4120×H12 |
| H1 = tanh(0.5 × (0.2113−0.0010 × f + 0.0000 × N−0.01422 × d)) |
| H2 = tanh(0.5 × (−0.1455 + 0.0008 × f + 0.0000 × N + 0.0080 × d)) |
| H3 = tanh(0.5 × (−0.0393 + 0.0002 × f−0.0000 × N + 0.0024 × d)) |
| H4 = tanh(0.5 × (−0.0819 + 0.0005 × f−0.0000 × N + 0.0038 × d)) |
| H5 = tanh(0.5 × (−0.0804 + 0.0000 × f−0.0000 × N−0.0002 × d)) |
| H6 = tanh(0.5 × (0.0587−0.0004 × f + 0.0000 × N+0.0021 × d)) |
| H7 = tanh(0.5 × (0.0033 + 0.0000 × f + 0.0000 × N−0.0003 × d)) |
| H8 = tanh(0.5 × (0.0538−0.0003 × f + 0.0000 × N−0.0031 × d)) |
| H9 = tanh(0.5 × (−0.0153 + 0.0001 × f + 0.0000 × N + 0.0005 × d)) |
| H10 = tanh(0.5 × (−0.0554 + 0.0003 × f−0.0000 × N + 0.0022 × d)) |
| H11 = tanh(0.5 × (−0.0851 + 0.0005 × f−0.0000 × N + 0.0042 × d)) |
| H12 = tanh(0.5 × (−0.0344 + 0.0002 × f−0.0000 × N + 0.0015 × d)) |
factors and responses are shown in Table 9. The ten runs are chosen due to the desirability factor near the unit. The first ten tests show that a high cutting speed and feed rate and a small tool diameter are suitable for reducing the delamination factor with desirability rates of 0.98 and 1.00 for HSS-TiN and BSD, respectively (Fig. 12a and b). Indeed, according to the highest desirability value equal to 0.97, the optimal drilling machining conditions according to Table 9 \( (f = 50 \text{ mm/min}, N = 1399.99 \text{ rev/min} \text{ and } d = 5.61 \text{ mm}) \) lead to minimal delamination \( (F_d) \) for HSS-TiN and BSD, whose values were 1.09 and 1.10, respectively.

The models obtained by the ANN method were retained for the resolution of the optimization problem using the genetic algorithm (GA) and for the search for the minimal multi-variable nonlinear constraint function \((f\text{mincon})\) using MATLAB software. Table 10 shows the results obtained from the optimization of the input parameters and \(F_d\) for the two drill geometries (HSS-TiN and BSD). The results indeed reveal that the response of the GA and \(f\text{mincon}\) parameters provide approximately similar values. The results for comparison between the response parameters \((F_d)\) obtained for the HSS-TiN and BSD tools with RSM and those predicted by the GA and \(f\text{mincon}\) algorithm are 1.08 and 1.03 obtained by

![Fig. 10 Comparison between experimental and predicted \(F_d\) with RSM and ANN models. a HSS-TiN and c BSD drills](image)

![Fig. 11 \(F_d\) residuals for RSM and ANN a HSS-TiN and b BSD drills](image)

**Table 8** Goals and parameter ranges for RSM optimization of cutting conditions.

| Condition       | Goal     | Lower limit | Upper limit |
|-----------------|----------|-------------|-------------|
| Feed rate, \(f\) (mm/min) | Is in range | 50          | 190         |
| Spindle speed, \(N\) (rev/min) | Is in range | 355         | 1400        |
| Drill, \(d\) (mm) | Is in range | 5           | 10          |
| \(F_{a(HSS-TiN)}\) | Minimise | 1.025       | 1.581       |
| \(F_{a(BSD)}\)       | Minimise  | 1.102       | 1.684       |
RSM, 1.04 and 1.05 in the case of GA and 1.04 and 1.09 for the function fmincon, respectively, confirming the relevance of the models and the adequacy of the results with those obtained by [21].

4 Conclusion

The present research focused on the development and optimization of jute fibre polymer composite delamination factors with two types of HSS-TiN and BSD drills. The results obtained above showed following conclusions:

- Based on the effects of the combination of cutting parameters in the drilling process, a combination of a low feed rate and small tool diameter is clearly needed to minimise the delamination factor
- The importance of the material and the feed rate in relation to the diameter of the drill are predominant on the delamination factor, and it has been noticed that spindle speed has no influence on the latter. The contribution of the different elements of the optimal drilling condition are as follows: feed rate (66.04%), drill diameter (10.54%) and spindle speed
- The quality of the optimization is considered good with an overall desirability factor of 97%
- The results of the predictive models and the experimental measurements are in good agreement
- The average error percentages between the model and the experimental results are 0.26% for the HSS-TiN drill and 1.01% for the BSD drill
- The ANN and RSM models applied to predict the cutting parameters in the drilling processes show very high agreement with the experimental data. The experimental results compared with those predicted by the RSM and ANN models indicate that ANN models are more accurate and produce excellent results

Indeed, manufacturers seek to obtain better machinability of their products, regardless of the material. This detailed study will make it possible to choose the most appropriate machining conditions to obtain better machinability.

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Declarations

Competing interests The authors declare no competing interests.

Ethics approval The work contains no libellous or unlawful statements, does not infringe on the rights of others, or contains material or instructions that might cause harm or injury.

Consent to participate The authors consent to participate.

Consent for publication The authors consent to publish.
Fig. 12 Ramp function graph of multi-objective optimization a HSS-TiN, b BSD and c HSS-TiN and BSD tools

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Fig. 13  Contour plot of desirability for $F_d$ for (a) HSS-TiN and (b) BSD tools.
Table 10 Comparing the response optimization techniques RSM, GA and fmincon optimization

| Machining parameters | Response parameters |
|----------------------|---------------------|
| \( f \) (mm/min) | \( N \) (rev/min) | \( d \) (mm) | \( F_d \) | Tools |
|----------------------|---------------------|
| **RSM optimization** |
| 50.000               | 355.002            | 6.047    | 1.0822 | HSS-TiN |
| 57.029               | 1023.600           | 5.034    | 1.0351 | BSD    |
| **GA optimization** |
| 51.162               | 1397.54            | 5.981    | 1.0401 | HSS-TiN |
| 51.091               | 1378.07            | 5.960    | 1.0489 | BSD    |
| **fmincon optimization** |
| 50.979               | 1397.52            | 5.992    | 1.0404 | HSS-TiN |
| 51.109               | 1391.06            | 6.012    | 1.0942 | BSD    |

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