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Review

Drilling Parameters and Post-Drilling Residual Tensile Properties of Natural-Fiber-Reinforced Composites: A Review

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Abstract: This review highlights the influence of parameters on the drilling characteristics of biocomposites including natural fibers. The particular structure of natural fibers, including their hierarchized geometry, which potentially causes fibrillation, can result in an increased chance of irregularity of the hole and a more complex mode of delamination or, in general terms, damage to the composite. On the other hand, to attain an effective junction of the laminates in a structure, a nut–bolt procedure must be selected, which requires the performance of a drilling operation. This is becoming increasingly important since the fields of application for natural fibers and their variety have been steadily growing in the last few decades. Additionally, adequately performed drilling operations can address considerations related to circular economy. The drilling characteristics evaluated herein include thrust force, torque, surface roughness, and the delamination factor at the entry and exit of the drilling tool. The variation in tensile strength, stiffness, and strain propagation due to the presence of open holes of various sizes, the number of holes, the holes' patterns, the effect of the type of fiber of the notches, the fiber architecture, and the fibers' stacking sequence in biocomposites have also been discussed.

Keywords: natural fibers; biocomposites; drilling; machinability; notch effect; open hole; residual tensile strength

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1. Introduction

1.1. General Considerations Regarding Natural Fiber Composites and Their Machinability

For sustainability purposes, the investigation of the possible replacement of synthetic fibers with natural ones, which can be derived from different parts of plants (bast, leaves, fruit, and seed hair) or from animals, such as silk and wool, has been widely diffused over the last few decades [1–3]. This can also be of interest, aside from considerations regarding the lightweight nature of most natural fibers, because of the relatively low cost of natural fibers, especially when they are, as is increasingly the case, by-products (if not waste products) of some form of industrial or agricultural system [4,5]. In most cases, they are also grown over short periods of time and are abundantly available (although, of course, on a local basis and with seasonal differences) [6–8]. Aside from the mechanical, physical, thermal, and chemical characterization of the fibers and the obtained composites, this process also requires studies regarding the effective use of these composites in engineering applications [9,10]. Studies on drilling provide critical examples with respect to these technical issues, as the creation of a hole by machining is an essential process in the manufacture and repair of composites [11,12]. To more effectively qualify the importance of this research, it must be clarified that the pre-forms that natural fibers can take are those of particles, or short fibers; woven structures; long fibers; and so on. As the result of this adaptability, natural fibers have emerged as a low-cost alternative reinforcement in polymer composites. This especially applies to sectors such as transportation, textiles, structural paneling, construction materials, the production of consumer goods, the automotive industry, structural paneling, the production of construction materials and low-cost housing, the creation of biomedical prostheses, etc. [13–15].

Natural-fiber-based composite materials must undergo two stages of manufacturing in order to be employed in structural applications. The first stage involves the fabrication of the laminates, which usually results in near-net shapes, while the second stage involves the adhesive bonding and machining of the fabricated composite laminate [16]. The second stage might include cutting, drilling, milling, turning, or combinations of each. It is essential to select a suitable fabrication technique and machining method and appropriate machining parameters to avoid damaging the material. In the case of high-performance structural applications of polymeric composites, such as aircraft wings, automobile frames, etc., the use of permanent mechanical joining methods such as welding or adhesive bonding is inevitable. Although adhesive bonding helps distribute loads and does not require the creation of notches, it is susceptible to temperature variation, UV degradation, and the prevalent moisture conditions in the environment [17,18]. Therefore, the best possible alternative is the use of temporary joining methods such as a nut/bolt mechanism [19,20]. However, the drilling of holes is mandatory to facilitate the permanent joining of two or more parts manufactured from polymeric composites.

1.2. Main Parameters Involved in Drilling of Polymer Composites and Their Application to Natural Fiber Composites

The perforation of polymer composites can be easily accomplished using a simple machine with a drill bit attached to its spindle. However, the true challenge lies in obtaining the undamaged specimen without delamination, microcracks in the polymeric matrix in the vicinity of the drilled hole, imperfections such as poor surface roughness around the hole, and fibers being pulled out from the polymer matrix. This can be achieved by optimizing parameters such as the spindle speed, the drill bit material, the lubricant used, etc. In practice, the factors that influence drilling performance can be divided into two categories: those linked to composite manufacturing and others specifically related to the drilling operation with regard to the geometry of the drill bit used or the modes in which it is operated in terms of velocity, feeding rate, etc. [21]. The optimization process can be implemented/improved through the use of analytical techniques, such as fuzzy logic methods, which typically employ Taguchi orthogonal arrays [22,23]. Consequently, grey relational analysis (GRA) can lead to the simultaneous optimization of all parameters, which jointly contribute to a general characteristic that expresses the effectiveness of drilling, i.e., the material removal rate (MRR). For example, this has been applied to two epoxy composites reinforced with natural fibers: jute/flax hybrids [24] and sisal basket weave fibers [25]. A notch is created when the spinning drill bit penetrates the substrate of the material, which is generally detrimental to the laminate's properties [26]. The drilling parameters must be compatible with the material's properties, such as the fibers, matrix, thickness, etc. Moreover, if the matrix being used is a thermoplastic material, high-speed drilling should not be employed, as the materials might be sensitive to heat and lead to the softening or melting of the matrix [27]. Therefore, selecting the right parameters is of utmost importance.

The parameters that can influence the drilling characteristics of polymer composites are summarized in Figure 1. It is noteworthy that many of these factors only limitedly refer to natural fiber composites, as the starting point is a reference to glass and carbon fiber composites. In particular, for those factors involving fibers, one would need to consider that the variations are mainly due to the corresponding applications involving a wealth of different natural fibers for the production of composites. In fields interested in the use of these materials, such as automotive/transportation-related fields, the need—despite all difficulties—to establish an overall picture of the fibers/cellulosic reinforcements available has been highlighted [28]. Regarding the matrix, although in principle the application of bio-based matrices would be desirable, for technical applications requiring precise hole-making, the use of an epoxy matrix with natural fibers is very prevalent [29]. The application of other matrices such as polyolefins still represents an issue to be solved via the typical compatibilization of the lignocellulosic system through methods such as the application of maleic anhydride. In particular, it has been recognized that scarce compatibility, leading to easier pull-out, has an obvious influence on machinability [30]. Only once these problems have been addressed and natural fiber composites adapted to a semi-structural use, such as in panels or laminates, can the focus of the analyzed factors be shifted to the drilling procedure and the drill's characteristics. This aspect represents a marked difference from glass and carbon fiber composites, where the acquisition of a composite with effective structural performance before the drilling operation does not normally represent a problem.

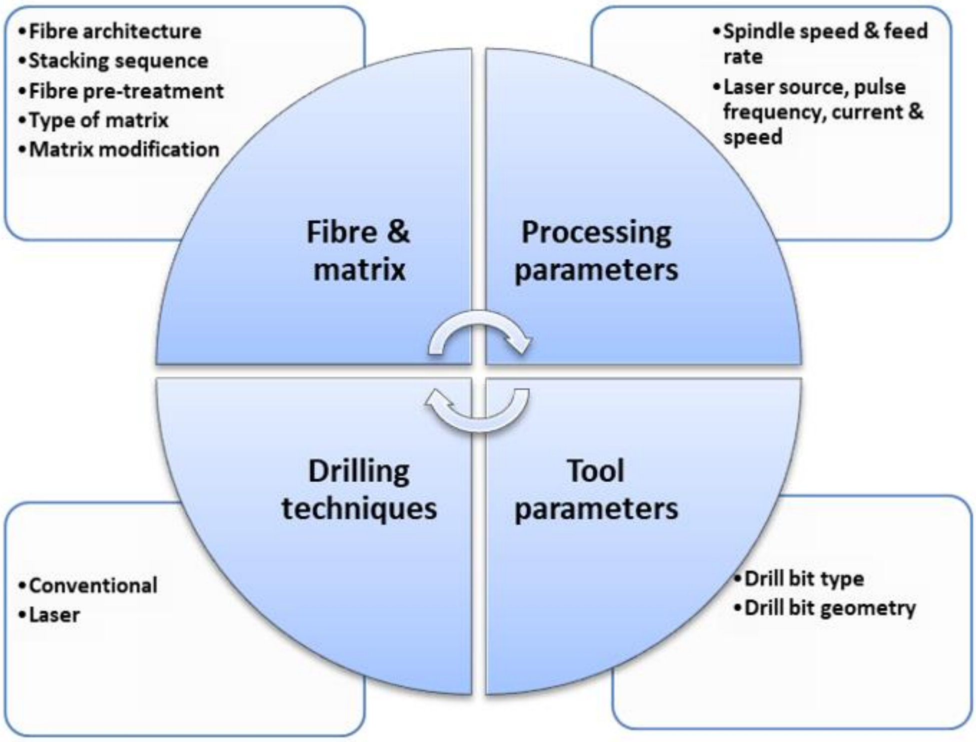

Figure 1. Parameters influencing the drilling characteristics of polymer biocomposites.

1.3. Drilling of Synthetic and Natural Fiber Composites: Specific Differences

There are also some studies specifically comparing synthetic and natural fiber's drilling behaviors. In particular, studies comparing Kevlar- and abaca-reinforced composites during machining have suggested that it is possible to apply different drill geometries, namely, candlestick and core bits, and still obtain appropriate performance, although the thrust forces are markedly different (28.6 N for abaca and 63.18 N for Kevlar composites) [31].

Another comparative study between hemp, jute, banana, and glass/polyester composites indicated that hemp fiber composites presented a lower level of damage after drilling according to their delamination factor and surface roughness [32]. The potential use of the same drill bit and diameter on both types of composites becomes particularly important due to the ever-growing diffusion of hybrid natural/synthetic fiber composites, for which drilling performance has also been studied. Some paradigmatical examples have been provided in order to report the extent to which these hybrid composite studies have been applied. One study compared the material removal rate during drilling between glass/bagasse and glass/novel kitchen waste hybrids [33], while another investigated the potential for the adhesive joining of sisal/jute hybrid composites with drilling damage in the overlapping area [34]. Studies on the drilling of hybrid composites will be presented alongside others in Section 2.

Drilling and other machining operations involve material removal, which reduces the strength retention of materials under various mechanical loads and significantly influences their in-service performance, leading to a high rejection rate of parts. This renders the selection of optimal drilling parameters even more crucial, such as in the case of flax-fiber-reinforced composites, especially when coupled with other machining operations such as waterjet cutting [35]. In a recent study on nettle-fiber-reinforced composites, it was observed that it is not possible to directly draw on facts established for the drilling of synthetic-fiber-reinforced thermoset composites for use toward natural-fiber-reinforced composites, even though epoxy is also widely applied to produce the latter [36]. This is not surprising, since the hierarchical structure of natural fibers renders them susceptible to fibrillation, i.e., the longitudinal splitting of fibers under the application of a shear force [37]. As a consequence of their peculiar structure in relation to synthetic fibers, some other factors must be considered, especially when dealing with the drilling performance of natural fiber composites. These include the effect of chemical treatment on the fiber characteristics and the possible use of drill bits with particular geometries (even those tailored for the specific composite) [38]. Hence, in order to estimate the acceptable loads that materials can withstand, the residual strength of materials with drilled holes and notches must be assessed [39].

Aside from traditional drilling techniques, non-traditional ones, such as abrasive aqua jet cutting (AAJC), laser drilling, and ultrasonic-vibration-assisted drilling, have been used on natural fiber composites. Notably, these methods are often found to be useful for innovative structural materials, such as for the application of AAJC to superalloys [40] or metal matrix composites [41]. However, even though the structural character of natural fiber composites is still under investigation, all of these non-traditional processes have been applied to them as well. Regarding AAJC, studies have investigated the effect of variable transverse velocity and pressure as well as the effect of hole diameters, abrasive flow rate, and stand-off distances [42]. In laser drilling, the effectiveness of the cutting process can be related to a number of operational parameters aside from cutting speed, such as laser power, gas pressure, and the position of the focal point [43]. Ultrasonic-vibration-assisted drilling is more specifically used for carbon-fiber-reinforced composites to overcome issues related to their brittleness, and it has only been tentatively applied to natural fiber composites [44].

This article discusses drilling characteristics and the parameters affecting them as well as the residual tensile strength (RTS) and the fatigue performance of biocomposites with notches and open holes and the ways in which to improve their drilling performance in view of more extended applications.

2. Performance Metrics

2.1. Definition and Significance of Principal Parameters for Damage Measurement in Drilling: Delamination Factor, Critical Thrust Force, etc.

The delamination factor is defined as a unitless ratio between two diameters: that of the delaminated area and the drill's nominal one [45]. Whilst the latter is obviously known, some difficulties can be encountered when measuring the former. A major issue is that it is unlikely for the delaminated area to be circular after drilling, while a second issue is that this area is typically not completely visible from the surface of the sample, hence its sectioning is often required, or in any case the acquisition of several measurements along the external thickness [46]. Most specifically, peel-up delamination occurs as the drill bit enters the uppermost layer, while push-down delamination occurs when the drill bit reaches the rear end, at which point the thrust force (TF) exceeds the material's inter-laminar strength. Among other parameters, the delamination factor is quite easily assessed and measured and offers indications with which to compare laminates with respect to their ability to withstand drilling when using the same drill [47]. In the case of natural fiber composites, the two delamination phenomena may have considerably different levels of non-uniformity concerning the fibers' local properties [48].

Thrust force and the torque generated in the direction of drilling can be measured using a dynamometer during the drilling operation. A critical thrust force, F_{crit}, under which no delamination is detected, has, for example, been modeled using flax-fiber-reinforced composites [49] to control the maximum possible feed rate, wherein it was equal to:

$$F_{crit} = 16 * \pi \sqrt{\frac{6 * G_{Ic} \times \delta}{13}} \quad (1)$$

where G_{Ic} is the critical strain energy release rate and δ is the bending stiffness of the composite. The thrust force and torque produced during the drilling of roselle/sisal hybrid composites were also predicted with good accuracy using an artificial neural network (ANN) [50].

To avoid causing excessive damage to natural fiber composites, thrust force and torque need to be minimized; accordingly, the effects of different parameters have been investigated. One of the critical aspects of the fabrication of natural fiber composites, and thus in their processing and machining, is the use of biomatrices, such as poly(lactic acid) (PLA). Therefore, the drilling performance of PLA/natural fiber composites was considered of interest and compared even favorably with high-density polyethylene (HDPE) composites filled with conifer sawdust [51]. In addition, in unidirectional bamboo fiber/PLA composites, it was discovered that with respect to other geometries (eight-facet and dagger), the slot drill induces minimum thrust force and torque with no detriment to the quality of the hole, while the drilling forces reduce the use of a high spindle speed and low feed [52].

2.2. Main Parameters Influencing Drilling of Natural Fiber Composites

Some studies have investigated the influence of drilling parameters on the damage inflicted on natural fiber composites. In particular, Belaadi et al. investigated the influence of the spindle speed (SS) (355, 710, and 1400 rev/min), feed rate (FR) (50, 108, and 190 mm/min), and tool diameter (5, 7, and 10 mm) of a brad and spur drill (BSD) on the delamination factor of jute/polyester composites [53]. The authors noted that a higher SS led to lower DF due to the reduction in the contact time between the drill bit and the composite. Both the FR and drill bit diameter were found to influence the DF, with the latter contributing to a greater degree due to the interference of the accumulated sheared composite chip around the drilled hole. This renders the tool less effective against the shearing-based removal of material from the composite. The optimal conditions for the minimization of the delamination factor with the different drilling parameters were obtained on a jute-and-coir-reinforced composite using a genetic algorithm and were found to be equal to 1397.54 rev/min for the SS, 51.162 mm/min for the FR, and 5.981 mm for the tool diameter, respectively [54]. Of course, the values obtained considerably depend on the natural fiber used in the composite; this is particularly important, because the range of natural fibers available has grown considerably in the last few years. In the case of epoxy composites manufactured using alkali-treated (1% NaOH) *Washingtonia filifera* fibers, a numerical model whose use led to a minimized delamination factor (1.035) suggested the use of a drill with a 5 mm diameter at a FR of 50 mm/min and an SS of 2500 rev/min [55]. Another fiber recently investigated for use in natural fiber composites was aloe vera, which was incorporated in a hybrid composite containing sisal fibers. Consequently, it was revealed that different tool diameters, namely, 6, 8, and 10 mm, and various spindle speed values, including 250, 500, and 750 rpm, were related to the delamination factor and surface roughness [56].

Jayabal and Natarajan performed drilling experiments on coir–polyester composites using a high-speed steel twist drill (HSS) with SSs of 600, 1200, and 1800 rev/min; FRs of 0.05, 0.20, and 0.35 mm/rev; and tool diameters of 6, 8, and 10 mm. In this case, the optimal parameters for which the axial force, torque, and tool wear were minimal were 600 rpm, 0.35 mm/rev, and 6 mm, respectively. The characteristics of chip formation (continuous, discontinuous, or mixed) were dependent on all three parameters and, when using optimal values, were mixed [57].

A comparative study evaluating different natural fiber composites based on date palms evaluated certain drilling factors, namely, the spindle and feed velocities and the drill material, comparing a drill with a titanium nitride protective layer, a drill with a carbide protective layer, and a super-high-speed steel drill [58]. The comparison was carried out in terms of the delamination factor, the cylindricity of the delaminated areas, and the circularity of the drilled holes; consequently, it was suggested that the feed rate value has a kind of directly proportional relationship with the delamination factor, while increasing the cutting speed affected such proportionality. This observation contrasts with the results obtained in a previous study on polylactic acid (PLA) drilling, where cutting speed did not appear to have a significant effect on the delamination factor [59]. It may be suggested that the presence of natural fibers produced this effect, which was likely due to the nonuniformity of their local properties, suggesting that limiting the time that the material is in contact with the tool via increasing the drilling speed might also reduce the extent of the damage. In practice, the intimate friction occurring during cutting can be modified by using tools with different surface coatings, as reported in [60] with respect to the drilling of flax fiber/polypropylene composites, indicating that drilling speed needs to be modified when applying different tools to natural fiber composites. On hemp-fiber-reinforced polyester composites, when using a 5 mm tungsten carbide drill bit, the influence of cutting speed on delamination was confirmed, while it was suggested that it should not exceed 2000 rpm [61].

In practice, natural fiber composites with a large variety of reinforcements were investigated with respect to their drilling properties. Some of the results obtained are reported in Table 1 with regard to a number of parameters reported in Figure 1 concerning drilling and the drill's characteristics in order to clarify the extent to which the influence of the above can be assessed via the quality of the hole obtained in the composite. To achieve this result, the table concentrates on those studies that provide clear evidence of the aforementioned parameters.

Table 1. Some studies on drilling into natural fiber composites and relevant hole quality parameters.

Composite	Main Results	Reference
Jute/epoxy	The major influence (88.19%) according to ANOVA results was reported to the drill diameter. Overall, the optimal characteristics were 6 mm drill size, 3000 rpm spindle speed, and 50 mm/min feed rate	[62]
Vetiver/polyester	Optimal conditions were obtained with spindle speed above 2800 rpm, feed rate of 0.2 mm/rev, and point angle between 80° and 120°, according to the lowest measured roughness (3.06 μm)	[63]
Pineapple/epoxy	Highest speed, lowest feed, and lowest drill diameter offered minimal thrust force	[64]
Sisal/banana/epoxy	Optimal conditions were 1500 rpm spindle speed, 50 mm/min feed rate, and a drill bit with 6 mm diameter	[65]
Sisal/epoxy/polyurethane	Optimal conditions were obtained with 8 mm drill bit, which played the largest role; 2700 rpm spindle speed; and 60 mm/min feed rate.	[66]
Luffa/epoxy	6 mm drill bit diameter, 2000 rpm spindle speed, and 10 mm/min feed rate minimized delamination	[67]

The pre-treatment of fibers, e.g., with alkali, can considerably reduce their roughness, which also applies to drilling damage; specific reviews exist on this aspect, e.g., [68]. It has also been suggested that the size of texture, and hence the coarseness of the natural fibers used for fabrication (in the cited example, jute), has an important influence on the delamination factor, which is likely connected to the variability of the drill's contact with the material [69]. The effect of treatment with a 2% solution of sodium hydroxide (NaOH) on the drilling properties of short kenaf fiber/poly vinyl alcohol (PVA) was studied in [70]. In particular, the comparative properties of the untreated and treated laminae are provided in Table 2. It is evident that the priority of the factors' influence on the properties is unchanged, while some variations can be noticed in the optimal values. However, the concentration of NaOH solution is not very large compared to other cases, which might limit the significance of these results. In the specific case of kenaf, it is remarkable that higher concentrations of alkali (up to 10% NaOH) yielded mixed results whenever stiffer fibers were required for composites manufacturing [71].

Table 2. Optimal characteristics for thrust force and torque in kenaf fiber/PVA composite (elaborated from [70]).

Characteristics	Untreated Fibers	Treated Fibers
Influence on thrust force	Point Angle > Chisel Edge Width > Speed > Feed Rate	Same
Minimum thrust force	Point angle: 118° Feed rate: 0.15 mm/rev Speed: 290 rpm Chisel edge width: 2 mm	Lower point angle of 118° Feed rate: 0.17 mm/rev Speed: 290 rpm Chisel edge width: 1 mm
Influence on torque	Feed Rate > Speed > Point Angle > Chisel Edge Width	Same
Minimum torque	Point angle: 108° Feed rate: 0.175 mm/rev Cutting speed: 580 rpm Chisel edge width: 2 mm	Point angle: 118° Feed rate: 0.15 mm/rev Cutting speed: 290 rpm Chisel edge width: 1.5 mm

2.3. Other Drill and Drilling Parameters Investigated

According to Choudhury et al., the drill bit geometry has the greatest impact on the thrust force (TF) compared to the other input parameters. Some of these geometries were compared, namely, 4-facet, 8-facet, dagger, step, and parabolic drill bits, using nettle/polypropylene composites with different combinations of feed rates and speeds of the drill bit. A parabolic drill geometry with low feed and high spindle speed proved to be the most suitable for obtaining low thrust forces [71]. This was confirmed through an analysis of variance (ANOVA) of the data in a study on flax-fiber-reinforced composites, where it was determined that the drill bit type and feed have the greatest influence on the thrust force. In particular, the delamination factor (67.27%) and surface roughness (74.44%) were significantly influenced by the choice of drill bit but not by the feed rate and spindle speed [72]. Further research on flax-fiber-reinforced composites included the application of a multicriteria study employing ANOVA, which evidenced that the ideal set of drilling parameters included a higher spindle speed, a lower feed rate, and a step type of drill bit geometry [73]. On the other hand, on jute fiber/polyester composites, the influence of spindle speed was found to be minimal, if not absent, when compared with the feed rate and drill geometry [74].

Celik and Alp used high-speed steel (HSS), titanium-nitride (TiN)-coated HSS, and a tungsten-carbide-coated (WC) HSS drill for the perforation of flax/epoxy and jute/epoxy composites [75]. According to their observations, for both the composites, the TF was lower for the TiN-coated HSS and WC than the conventional HSS without coating. Among the composites, jute/epoxy composites registered higher TF values at the increasing spindle speed (SS) and feed rate (FR) than the flax/epoxy composites. However, the thrust force declined with an increasing SS speed and vice versa for a higher FR for both jute- and flax-based composites. Similarly, in the case of thermosetting matrices, Patel et al. used

HSS to drill into banana/polyester composites at a FR of 0.1 to 0.3 mm/rev, an SS from 1000 to 3000 rpm, and drill point angles of 90, 104, and 118°, respectively. The peel-up DF declined at a higher SS and higher point angle and vice versa for the FR. More precisely, the optimal values for the thrust force and delamination factor were a drill point angle of 90°, a 1000 rpm cutting speed, and a 0.1 mm/rev feed rate [76].

Moving on to the use of thermoplastic matrices, Bajpai and Singh used both high-speed steel (HSS) and trepanning drilling on sisal/polypropylene (PP) composites. At a constant feed rate, torque decreased with the increase in spindle speed (SS) for the trepanning drill, while it was relatively constant for the HSS. Moreover, at a constant SS, torque was revealed to increase with a higher FR for both drilling schemes. SS had almost no influence on thrust force (TF) for the HSS and trepanning drill, whereas it was found to be higher as the feed rate increased. The difference in TF and torque with respect to the SS and FR arose from the difference in the cutting mechanism between the drill bit geometries of the HSS and the trepanning drill; thus, it was concluded that the use of trepanning drilling was preferable for the sisal/PP composites [77]. Bajpai et al. drilled into sisal/polylactic acid (PLA) composites and Grewia Optiva/PLA composites using parabolic, Jo, and HSS drill bits at SSs of 900, 1800, and 2800 rpm and FRs of 0.05, 0.12, and 0.19 mm/rev. On the other hand, Grewia Optiva/PLA composites displayed slightly higher TF and torque than the sisal/PLA composites with the use of a single drill bit and different processing parameters. However, between the drill bits, the Jo drill displayed the maximum thrust force and torque followed by the parabolic and HSS drills [78]. Diaz-Alvarez et al. employed a 6 mm diameter HSS drill with 70, 80, 90, 100, 110, and 118° drill point angles to drill flax/PLA composites. The authors observed that the TF increased with the increase in the drill point angle and that the increase in the TF was more prominent with respect to the increase in FR than due to the increase in SS. However, the thrust force could be significantly higher for the maximum SS employed. The peel-up DF at the entry point and the push-down DF at the exit were found to be lower for drill point angles of 70, 80, and 90° and continued to increase with the increase in the drill point angle up to 118° [79].

In the case of lignocellulosic powder filler, which is typically employed to improve the hardness of a polymer, Azuan et al. used HSS, end mill, and brad-and-spur drills (BSDs) to drill rice husk/polyester composites at FRs of 0.1, 0.15, and 0.2 mm/rev, while the SS was changed from 1500 to 2000 and 2500 rpm. The push-down delamination factor (DF) was the lowest for the HSS drill followed by end mill and BSD drills. In addition, the push-down DF showed an increasing trend with respect to the increase in the feed rate, while the higher cutting speed hardly made a difference [80].

3. Residual Tensile Strength (RTS) and Residual Flexural Strength (RFS)

3.1. Influence of Notch and Drilled Open Hole

Regarding post-drilling performance, in the case of natural fiber composites, it is also essential to study the progression of damage caused by the drill's perforation of a laminate. It has been recognized, e.g., in the case of kenaf/polyester composites, that the evolution of damage is very similar to the process observed for kenaf/glass hybrid composites, starting with a matrix failure process and only then propagating to the fiber–matrix interface [81]. Gobi Kannan et al. studied the RTS of unidirectional flax/polypropylene composites post-drilling by varying the fiber orientation ($(0)_6$, $(\pm45)_6$, and $(0/90/0)_S$) and the notch dimensions (central open holes with 2 mm and 4 mm diameters). A significant drop in RTS was observed as the notch size was increased from 2 to 4 mm, constituting increases equal to 7% and 46%, respectively. Regarding the fiber architecture, the composites with unidirectional, cross-ply, and angle-ply fibers showed 16%, 13%, and 9% decrements in RTS due to the drilling of a hole 6 mm in diameter. Beyond strength retention, both the tensile strength and the notched tensile strength of the composites corresponded to the following order: $(0)_6 > (0/90/0)_S > (\pm45)_6$. The highest tensile strength was observed for the composite with unidirectional fibers due to the existence of more fibers in a long fiber form in the +direction of the applied load. In contrast, the intermediate strength for the cross-ply laminate was due to the moderate number of fibers in the loading direction, while the number of fibers along the loading direction was even lower for the angle-ply laminate [82].

Hao et al. investigated the performance of kenaf/polypropylene composites with an open hole and a pin-filled hole under a tensile load. The authors assessed 3 mm and 6 mm thick specimens with various hole diameters (D) represented as the ratio of width (W) to diameter (W/D = 6, 3, and 2). Their results indicated that increasing the composite's thickness from 3 to 6 mm delayed the onset of failure; however, the load at which the composite failed and the maximum displacement did not experience a proportionate increase despite the better loadbearing characteristics observed in the thicker composite specimens. On the other hand, the pin-filled hole specimens exhibited better strength than the open-hole specimens, with a W/D = 3, and no significant influence on the stiffness. As the hole size increased, both the failure load and maximum displacement dropped significantly regardless of the open hole and pin-filled hole [83].

Ranjith et al. investigated the RTS of jute/epoxy-based composites with one, two, and three holes of an identical diameter that were adjacent to each other. Furthermore, they also covered the open holes with a M6 bolt prior to the tensile tests. It was observed that increasing the number of holes reduces the tensile properties of the material. Thus, covering the drilled hole with an M6 bolt might be only limitedly helpful as noted from the material's slightly higher strength retention, which highlighted the issues in improving residual tensile strength [84].

To summarize the above findings, in the previous studies, the tensile strength of the laminates was assessed with one or a few circular holes with varying diameters from 1 to 12 mm. The general observation was that the retention of the tensile strength was greatly dependent on the number of holes and hole diameters as opposed to the fiber type and resin characteristics. In a recent study, Bale et al. found that the hole pattern can also significantly influence the tensile strength and failure characteristics of the composites. The hole patterns investigated for lontar fiber/polyester composites are shown in Figure 2, showing (a) a central hole of 5 mm; (b) two holes parallel to the loading axis; (c) two holes perpendicular to the loading axis; (d) four holes in a diamond pattern; and (e) four holes in a square pattern. The composite with four holes in a square pattern (Figure 2e) showed superior tensile strength followed by the composites with a single hole (Figure 2a), a four-hole diamond pattern (Figure 2d), and double holes (Figure 2c,d). The variation in tensile strength was mainly attributed to the stress distribution within the composite and localized stress concentration regions around the hole. The composites with double holes experienced larger strain and exhibited the lowest strength, and their failure was initiated in the vicinity of the hole and transversely with respect to the direction of the applied load. In the case of the composite with four holes, failure was not initiated around the hole. This could be related to the redistribution of stress within the specimen such that failure occurred in the region away from the holes while the contours of the holes remained prevalently intact. Thus, better strength retention was observed in that last case [85].

The previous studies were limited by the fact that they studied hole patterns either in the center of the specimen or distributed within the boundary of the specimen. However, Fontes et al. made a semi-circular lateral notch (of 3 mm diameter) on the edge of a specimen along the horizontal edge and compared the data with a central notch of 6 mm in diameter made in jute/glass hybrid composites. The study concluded that both the notches had a negative impact on the composites' tensile strength, as shown in Figure 3. The specimen with a lateral notch showed a lower RTS regardless of the fiber orientation. L1H, L1N, and L1U represent $\pm 45^\circ$ orientations in the uppermost and lowest layer of the laminates with an open hole, a semi-circular lateral notch, and without a hole. L2H, L2N, and L2U represent $0/90^\circ$ orientations in the uppermost and lowest layer of the angle-ply laminates with an open-hole, a semi-circular lateral notch, and without a hole. Irrespective of the fiber orientation and notch pattern, the composites displayed both fiber pull-out and only later presented a gage-middle fracture, as shown in Figure 4a–d [86].

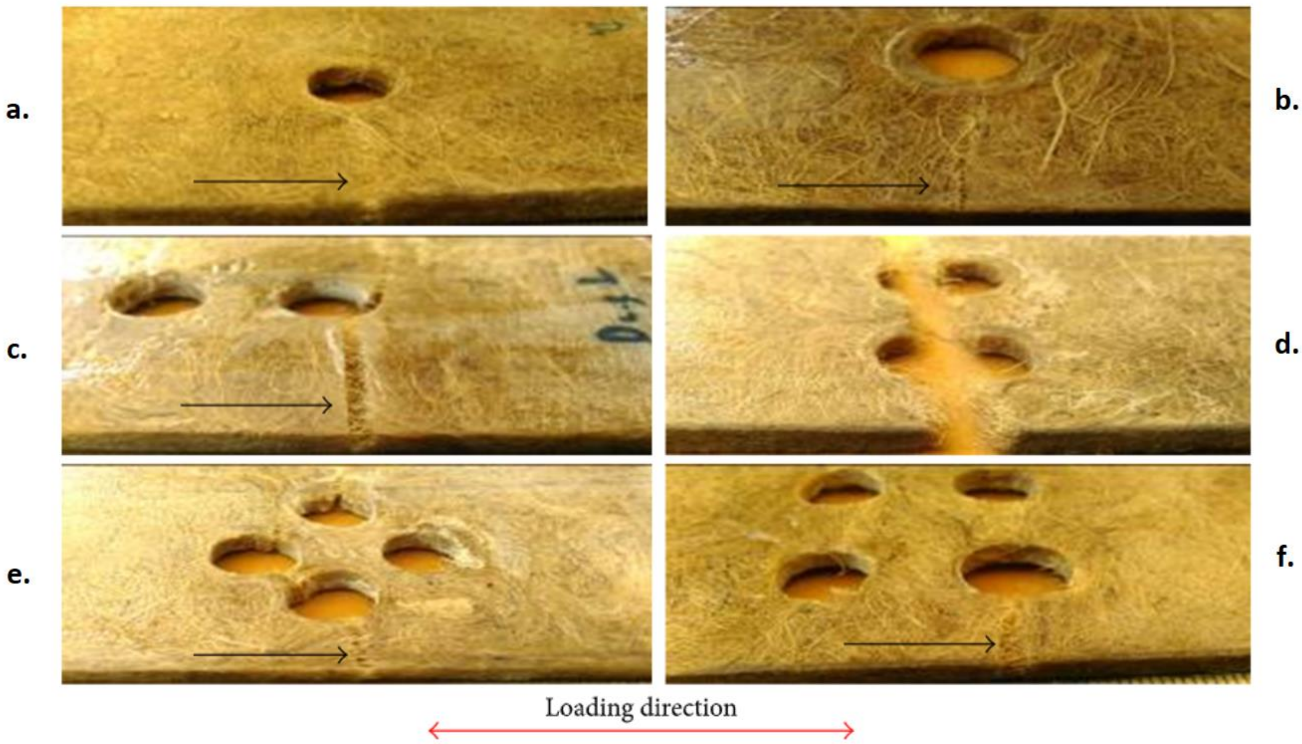

Figure 2. Hole patterns of the lontar fiber/polyester composites and their corresponding failures: (**a**,**b**) central hole of 5 mm, (**c**) 2 holes parallel to the loading axis, (**d**) 2 holes perpendicular to the loading axis, (**e**) 4 holes in diamond pattern, and (**f**) 4 holes in square pattern [85].

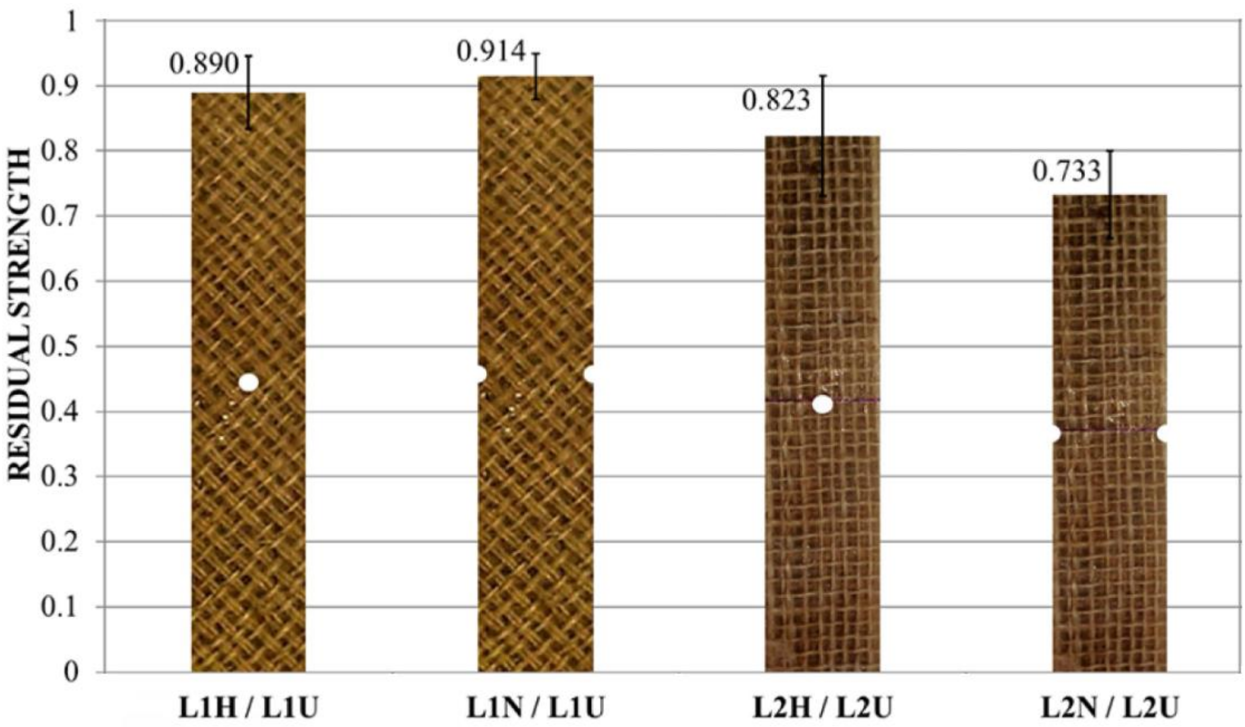

Figure 3. Residual strength for different fiber orientations and positions of a hole [86].

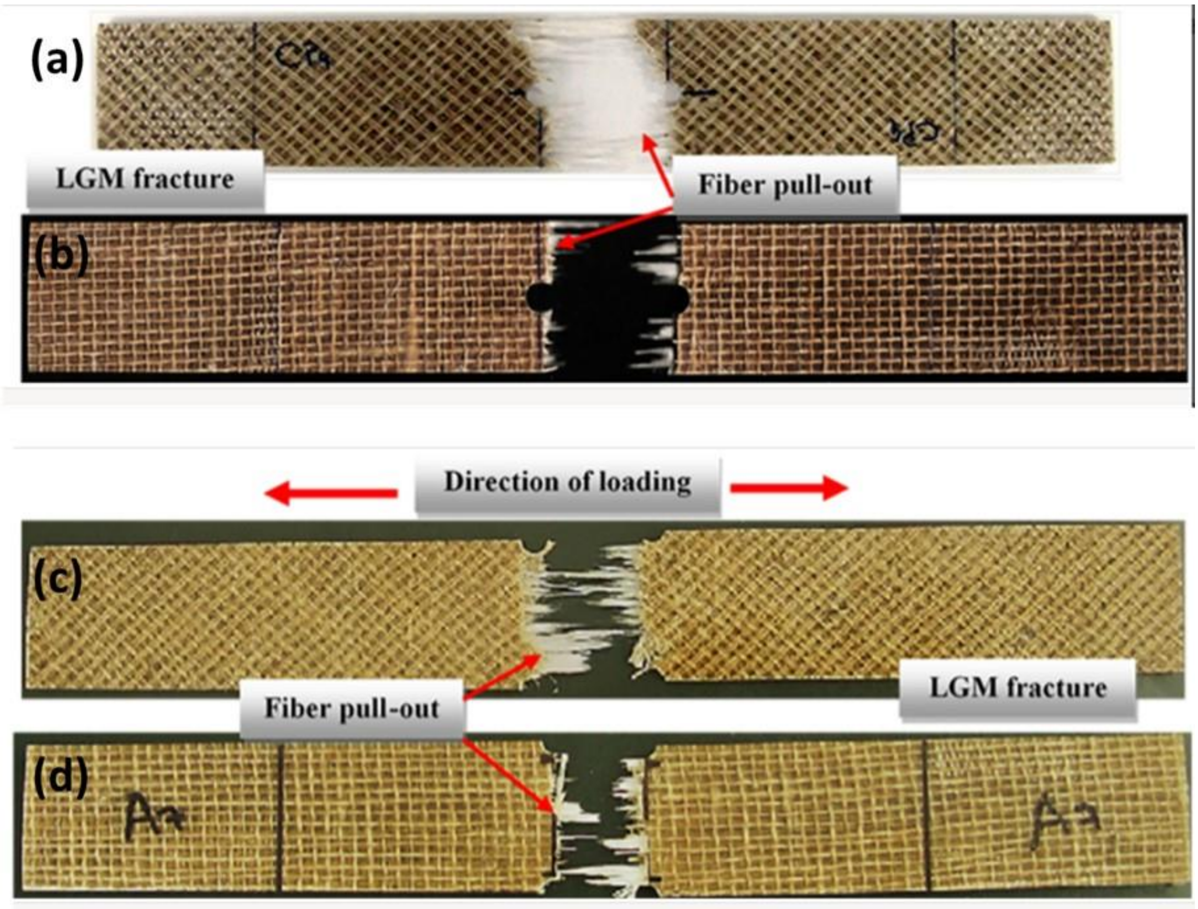

Figure 4. Failure pattern in the jute/glass hybrid composites in the uppermost and lowest layers of the laminate: (**a**) ±45° orientation with open hole, (**b**) 0/90° orientation with open hole, (**c**) ±45° orientation with a semi-circular lateral notch, and (**d**) 0/90°-oriented angle-ply laminate with a semi-circular lateral notch [86].

In the case of flax fiber composites, residual flexural strength was also investigated, for which the influence of the notch dimension was shown when using a High-Speed Steel (HSS) drill bit of 6 mm and 8 mm in diameter. This highlighted some reduction in flexural strength with the increase in the size of the drill bit, yet it was less significant than that observed between undrilled and drilled samples [87].

3.2. Enhancement of RTS

3.2.1. Hybridization

In some cases, as suggested above, the properties of natural fiber composites are not sufficient to match the requirements of the envisaged application. In this case, they are typically used in polymer composites in combination with other higher-performing fibers, such as glass [88,89], carbon [90], Kevlar [91], and basalt [92]; this can also be seen as a strategy to mitigate the effect and the challenge of the substitution of synthetic fibers with natural fibers. The obtained materials are defined as hybrid composites. This has obviously been the case in drilling as well, which is a particularly demanding and possibly damaging process. However, this strategy has allowed for the introduction of some natural fibers, which are normally not suitable for the manufacture of machinable polymer composites; this is the case for mulberry silk, which has been coupled with glass [93].

In particular, Salleh et al. studied the effect of an open hole on the tensile properties of kenaf and kenaf/fiberglass composites with drilled holes of 1, 4, 6, 8, 12, and 16 mm in diameter. The results showed that hybrid the kenaf/fiberglass composite showed good tensile strength retention, indicating a positive effect of hybridization. The strength retention declined with the increasing hole size irrespective of the composite investigated. The authors also mentioned that they heard a cracking sound during failure around the hole followed by fiber/matrix debonding. The polymer matrix failed initially (as shown in Figure 5), and shear damage progressed until fiber–matrix de-bonding occurred followed by fiber ruptures or pull-outs, which, finally, led to failure [94].

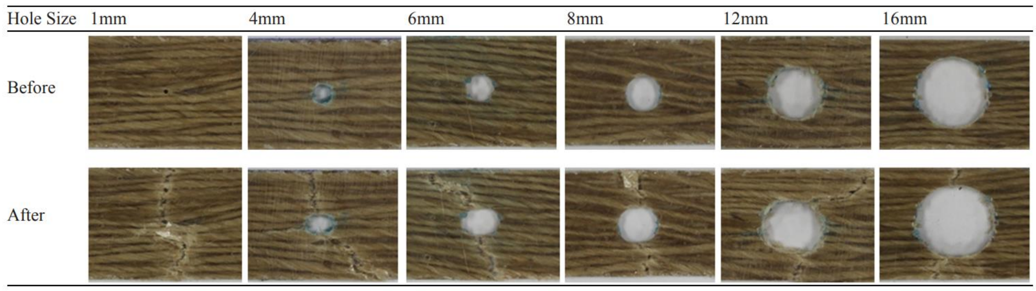

Figure 5. Front view of specimens with holes of different diameter before and after tensile test [76].

In coir/glass-fiber-reinforced hybrid composites, the influence of the stacking sequence on the residual tensile strength post-drilling was studied by Tamer et al. Both the unnotched laminates and the laminates with open holes showed better tensile strength following the introduction of glass fabric into the coir-based composites. However, it was also observed that both the number of layers (and hence the thickness) and the stacking sequence played a deciding role in the stiffness characteristics of the hybrid composites [95].

3.2.2. Nanofillers

As filler materials for polymer composites, nanofillers offer significant advantages in the fields of material science and polymer composites, including thermal insulation, flame retardancy, enhancements in mechanical properties, and reduced moisture diffusion, that can dramatically improve the material performance and service life of natural-fiber-reinforced composites. Nanofillers such as nanoclay, silicon carbide (SiC), silica aerogel, titanium dioxide (TiO_2), carbon nanotubes, aluminum oxide (Al_2O_3), etc., have been used in various proportions and have been proven to have enhanced the performance of biocomposites [96]. There is a considerable scope for research into the assessment of the performance of drilled nanocomposites, for which the mechanism that enhances strength retention and the mode of failure can be unique for each type of nanofiller. Hence, this needs to be explored such as it has been for the introduction of graphene into jute/epoxy composites subject to drilling, which has been investigated alongside the effect of fiber treatment [97]. Another major success in improving the circularity of the hole created during drilling was obtained on jute/sisal hybrid epoxy composites by the addition of 10% silicon carbide [98] (Figure 6).

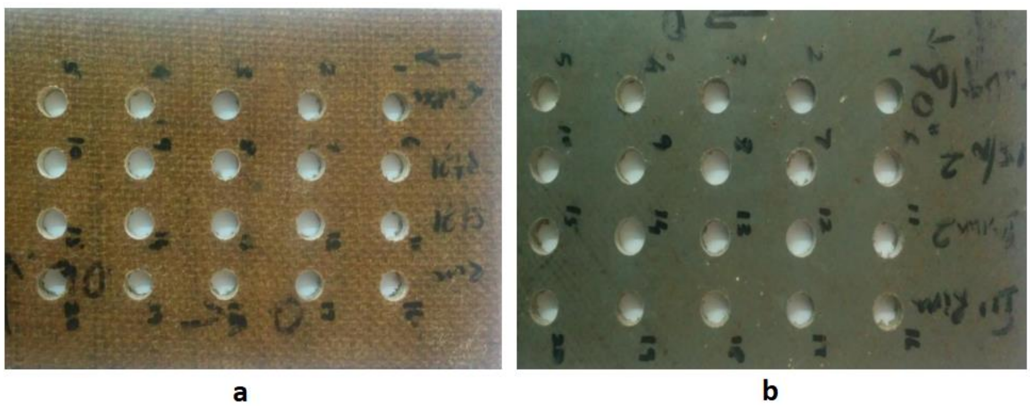

Figure 6. Holes drilled in jute/sisal hybrid composites: (**a**) without SiC filler; (**b**) with SiC filler [98].

Prakash et al. used a hand layup technique to fabricate a basalt/cashew nutshell liquid (CNSL)/epoxy resin composite mixed with equal amounts of SiC and banana fiber particulates (BNP), respectively. Laminates with a central hole of 6 mm in diameter and without a hole were subjected to tensile tests. Consequently, the authors reported 20% and 35% losses in tensile strength for the basalt/CNSL/epoxy/BNP laminate and Basalt/CNSL/epoxy/SiC laminate with holes compared to the specimens without holes. Among the investigated laminates, the composite with SiC filler presented superior tensile strength and a better retention of tensile strength with an open hole. The fillers were also found to influence the failure under tension for the notched laminates. The basalt/CNSL/epoxy/BNP laminate showed typical failures such as fiber breakage and cracks that were initiated around the vicinity of the hole and propagated along the width perpendicular to the applied load. In contrast, crack growth initiated around the hole and propagated along the length of the Basalt/CNSL/epoxy/SiC laminate [99].

3.2.3. Fiber Surface Modification and Use of Coupling Agents

To improve the compatibility between the polymer matrix and natural fibers, various fiber pre-treatment techniques, such as alkylation, acetylation, and the use of a coupling agent, namely, maleic anhydride (MA), can be employed [100]. Fiber pre-treatment is used to improve a composite's mechanical properties by modifying the fiber surface via the removal of fiber constituents, such as hemicellulose, pectin, lignin, and other impurities, such that the modified fiber surface more effectively promotes mechanical interlocking between the natural fibers and the polymer matrix. In the specific case of maleic anhydride, the wettability between the polymer and matrix improves via grafting, in which the coupling agent forms covalent bonds with the polymer and fiber [101].

In their study, Kannan et al. incorporated MA into a PP matrix and investigated the open-hole-related tensile properties of a flax/PP laminate. The strength retention characteristics under a tensile load did not improve for the laminates with open holes, while the undrilled laminates infused with MA exhibited superior tensile strength and stiffness compared to the undrilled laminates without MA [102].

There are hardly any studies on the use of fiber pre-treatments and coupling agents, specifically in the polymer matrix, on the RTS of biocomposites. The mechanism behind the strength retention characteristics also needs to be addressed.

4. Post-Drilling Fatigue of Natural Fiber Composites

In the case of a cyclical fatigue load applied post-drilling to natural fiber composites, it has been noticed that irrespective of the fiber orientation in the laminates, three possible modes of delamination are generated during loading. These are peel-up, push-out, and secondary delamination, and they were observed in bamboo fiber polyester composites [103]. The quality of the holes obtained for the front and back surfaces are reported in Figure 7. In recent years, more specific data have started to be obtained on the fatigue performance of drilled natural fiber composites. A study on carbon/flax-hybrid-reinforced laminates increased the level of concern about the application of non-traditional drilling procedures such as waterjet cutting, which offered a shorter fatigue life, particularly for cross-ply laminates (0/90 and $\pm$45) compared to conventional ones [104]. When dealing with the long-term behavior of natural fiber composites, other issues become important, such as the effect of hygrothermal aging on post-drilling fatigue; for short birch fiber/high density polyethylene (HDPE) composites, the influence of the treatment on the composites' fatigue performance was demonstrated to be minimal, which was a promising result with respect to the possible fabrication of spur gear using this composite [105]. In this respect, silane treatment was also investigated, showing some success in improving the fatigue performance of machined betelnut fiber/leather/chitin composites, partly by compensating for the complexity of the hybrid material [106]. Further information was also offered in a recent review on the fatigue of hybrid natural fiber composites [107].

Figure 7. Drilled holes of different diameters and accuracies in bamboo/polyester composites [103].

5. Conclusions

From the literature review of the published works on the drilling characteristics and residual tensile strength (RTS) of biocomposites with an open hole and notches, the following considerations can be drawn:

- Drilling characteristics: The drilling performance of the biocomposites was dependent on processing parameters such as the spindle speed, feed rate, and the drill bit diameter and its geometry. The use of a low-to-moderate spindle speed and a lower feed rate reduces the delamination at the entry point and exit and results in lower thrust force and torque. Statistical tools such ANOVA and grey relational analysis can be used to find the optimum input parameters based on the output variables.
- Increasing the notch dimensions creates a greater stress concentration around the hole, thus resulting in reduced tensile strength (RTS) and stiffness. Additionally, the type of fiber, the fiber's orientation, and the fibers' stacking sequence also significantly influence the RTS. Varying the number of notches and the position of the notches results in a lower retention of tensile strength, while materials with a pin-filled hole showed minimal or slightly better retention of strength depending on the hole's configuration when filled with pins.
- In the case of composites with a central hole, a transverse crack initiates near the edges of the hole and propagates further as the loading increases until the point of failure. Other typical failures such as fiber breakage, fiber pull-out, fiber/matrix debonding, and delamination between the laminae in the laminate were reported based on microstructural images of the fractured specimens.
- The addition of nanofillers can lead to better retention in the tensile strength of open-hole laminates and delay the onset of failure. The initial crack formed around the edge of the hole propagates along the length of the composite at an angle to the applied load in contrast to the typical transverse crack.

To summarize, the existing studies in the literature have mainly focused on the type of fibers, their architecture, their stacking sequences, notch patterns, and various hole diameters. The effect of drilling on the properties of various natural fiber composites was mainly elucidated via the study of delamination and the "quality of the hole", while some studies have been conducted on residual tensile strength and, much more limitedly, on post-drilling fatigue. In this respect, the influence of various nanofillers and fiber pretreatments on the RTS, failure mechanisms, and failure modes of biocomposites is still limitedly understood and requires further investigation in view of the increasing number of natural fibers yet to be investigated and established. It is also generally recognized, and is a fact that may lead to further developments, that although drill bits used for synthetic fiber composites can also be used in natural fiber composites, the realization of an optimal degree of machinability of natural fiber composites might require the tailored design of drill bits optimally adapted for application on these materials.

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