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Review

A review on the machining of polymer composites reinforced with carbon (CFRP), glass (GFRP), and natural fibers (NFRP)

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Abstract

Composite material consumption is booming and is expected to increase exponentially in many industrial applications such as aerospace, automotive, marine and defense. However, in most cases, composite products require further processing before they can be used or assembled. Machining of composite materials is extremely difficult due to their anisotropic and non-homogeneous structure. This paper provides a comprehensive review of the literature on composite materials and their machining processes, such as turning, milling and drilling. Damage related to these processes is also discussed. The paper is divided into seven main parts; the first, second and third parts give a brief overview of composite materials, reinforcements used in composite materials and composite manufacturing methods, respectively. The fourth part deals with post-processing machining operations, while the fifth, sixth and seventh parts are devoted to the machining of carbon fiber reinforced polymer composite, glass fiber reinforced polymer and natural fiber reinforced polymer composites, respectively. An analysis of the factors that influence the machining and the machinability criteria used for these materials is also presented, with particular emphasis on cutting forces, tool wear, delamination and surface finish. Non-traditional manufacturing methods are not discussed in this paper.

Keywords Composite materials · CFRP · GFRP · NFRP · Machining · Tool wear · Surface damage

1 Introduction

The composite materials sector is booming to the point that it is currently difficult to find an industry that does not leverage the benefits provided by the materials, which means that the sector must meet the demands of a constantly changing market. In these composites, several immiscible materials are arranged together, with the qualities of each constituent complementing those of the other to form materials with increased properties. They thus have many advantages, which allow them to compete directly with so-called conventional materials such as metals or alloys [1, 2]. They are used in many industrial applications thanks to their excellent mechanical and electrical properties and to their low density as compared to those of metallic structures [3].

Aerospace is a perfect example of a sector witnessing the emergence of composite materials [4, 5]. The success of FRP composites in this sector is mainly due to their very high strength-to-weight ratio [6, 7], allowing to significantly reduce the weight of aircraft components, and fuel consumption by extension, while maintaining similar resistance properties.

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According to Halpin [8], there are about 6–7000 components that are suitable for conversion from cast metallic to molded composite parts. FRP composites can also be used as patches for repairing or replacing metallic and non-metallic airframe structures damaged due to cracks and corrosion [9–12]. The repair process generally involves the attachment of a reinforcing patch with adhesively bonded fiber reinforced composites [13, 14].

By definition, a composite material consists of the mixture of two or more materials with different and complementary properties. The mechanical performance of fiber composites is directly related to the mechanical characteristics of their constituents: the matrix, the fibers and the fiber-matrix interface. Most often, a reinforcement is embedded in a matrix, allowing to obtain a material with properties providing rigidity and shape to the structure. The matrix penetrates between the fibers and isolates them from each other, and as a result, individual fibers can act separately, which helps to stop or slow the propagation of a crack [15]. However, its main role is to transfer mechanical forces from one fiber to another. The rigidity of a composite is ensured mainly by the fibers, which have much higher mechanical characteristics than the organic matrix. Therefore, the reinforcement contributes to improve the mechanical strength and stiffness of the material, while the matrix performs the dual role of transferring loads to the reinforcement, lending the structure its geometric shape, covering the reinforcements, and protecting them against the ambient environment [15, 16]. Epoxy resins are the most commonly used matrices for the development of advanced composites due to their excellent properties, including high electrical insulation, superior heat and chemical resistance, high mechanical resistance, low toxicity, low cost, good dimensional stability and ease of manufacturing [17–21]. They are usually chosen for advanced composite applications based on two different criteria, namely, glass transition temperature and epoxy equivalent weight [22, 23].

In the present review paper, the machinability of CFRP, GFRP and NFRP composite materials in turning, milling, trimming and drilling processes are addressed, and the outcomes of the studies conducted in this respect are compared. The reinforcement type and the manufacturing methods are discussed. The effect of fiber orientation on the machining response is also studied. Furthermore, the influence of the cutting tools geometries and materials on composite cutting is also examined in this work. Based on the literature studies, the optimal cutting conditions for each type of composite are presented. Additionally, the most important findings from the literature are analyzed in detail to allow commenting on the current trends in the machining of each kind of composite. Finally, a comprehensive review on the modeling of composite machining is performed, with a focus on the prediction of surface roughness, tool wear, cutting forces, cutting temperatures and machining induced sub-surface damage.

2 Reinforcements used in composite materials

Many reinforcements are available for composite materials, and are mainly categorized as synthetic or natural fibers (Fig. 1). A detailed and comprehensive fiber classification list can be found in [24, 25]. Usually, glass or carbon fibers serve as reinforcements for known and frequently used composites. Carbon fibers have very good mechanical characteristics while having a low density and excellent resistance to high temperatures. Further, they are able to retain their mechanical characteristics up to a temperature of approximately 1500 °C in a non-oxidizing atmosphere.

Recently, other reinforcements based on natural and vegetable fibers (flax fibers, in particular) have emerged. The new opportunities these provide are being leveraged and used in various fields of application. The form of reinforcements as well as the diameter, aspect ratio, orientation and content of the fiber also have a significant impact on improvements of mechanical composites properties [26–37]. Reinforcements can be classified into four distinct forms, namely, continuous fiber laminated composites, discontinuous fiber (whisker reinforcements), particulate reinforcements and woven composites [29, 38–42]. Depending on the composite manufacturing process used, continuous fibers are usually aligned and have a specified orientation, while discontinuous fibers are generally randomly

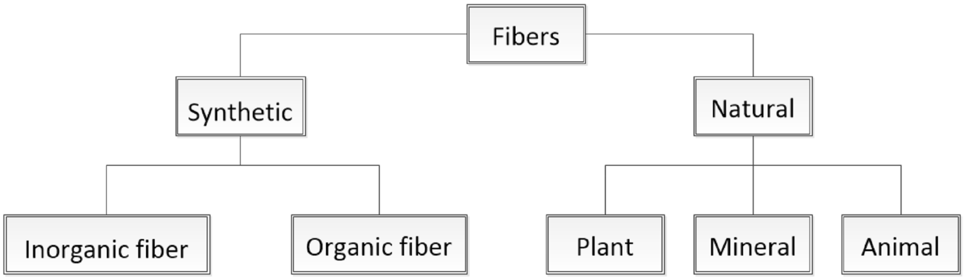


Fig. 1 Classification of fibers

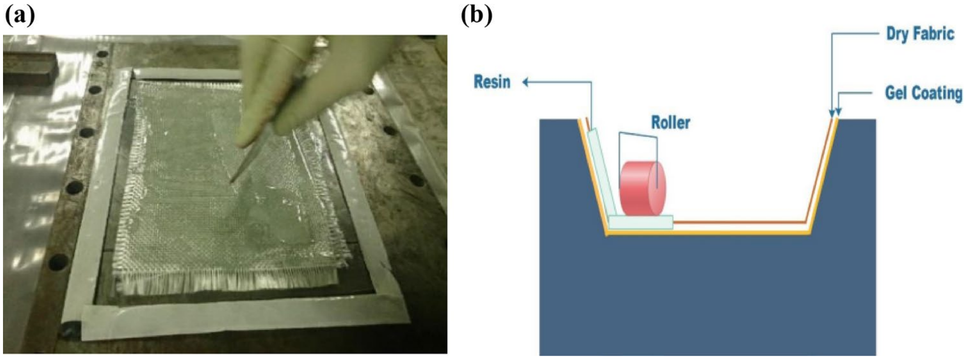


Fig.2 Hand layup process. **a** Photo reproduced from [47] under open access license. **b** Schema reproduced from [48] under open access license

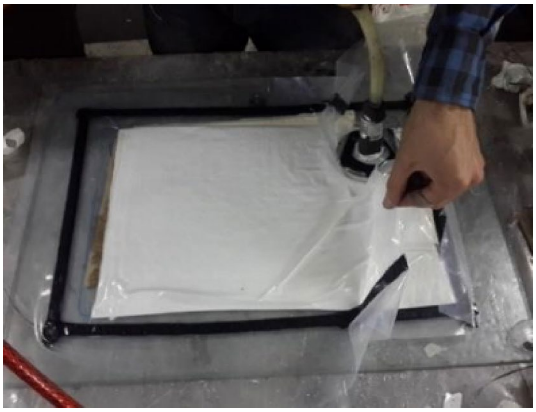


Fig. 3 Vacuum bag reproduced from [47] under open access license

oriented [27]. Furthermore, the strength of discontinuous fiber composites is about 20% lower than that of continuous ones [28, 38, 43]. Long fiber composites are anisotropic, whereas particulate composites are mostly isotropic [29, 38, 44]. Being isotropic, particulate composites exhibit identical material properties in all directions, while long fiber composites exhibit properties that are different in diverse directions [27, 29, 45, 46].

3 Composite manufacturing methods

The mechanical and thermal characteristics of parts made of composite materials depend not only on the constituents of the composite, but also on the manufacturing process, the conditions of use, the volume of production and the geometry of the part. Composite parts are usually manufactured by molding with advanced techniques in order to produce near-net-shape complex components. The literature provides several manufacturing methods for composite materials. The hand layup (Fig. 2), vacuum bag molding (Fig. 3), resin transfer molding (Fig. 4) and pultrusion (Fig. 5) are the most common primary manufacturing methods for FRP. The choice of a particular fabrication method for a specific part will therefore depend on the materials, the part design and the end-use or application.

Despite the rapid development of these shaping processes, the methods still produce only rough shapes with coarse tolerances. Hence, machining operations are most often required to obtain functional surfaces that are difficult (or even impossible) to achieve by the shaping process. Because a lot of near-net-shape machining is performed with high speed machining at both higher feed rates and higher cutting speeds, controlling machining responses is a challenge.

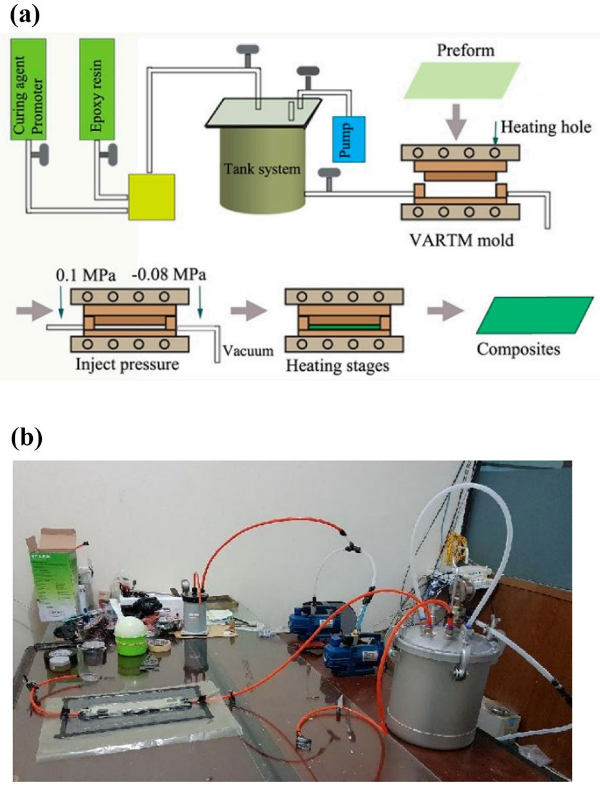


Fig. 4 Resin transfer molding (RTM). **a** Schematic illustration of the RTM process reproduced from [49] under open access license. **b** Photo of RTM with vacuum bagging reproduced from [50] under open access license

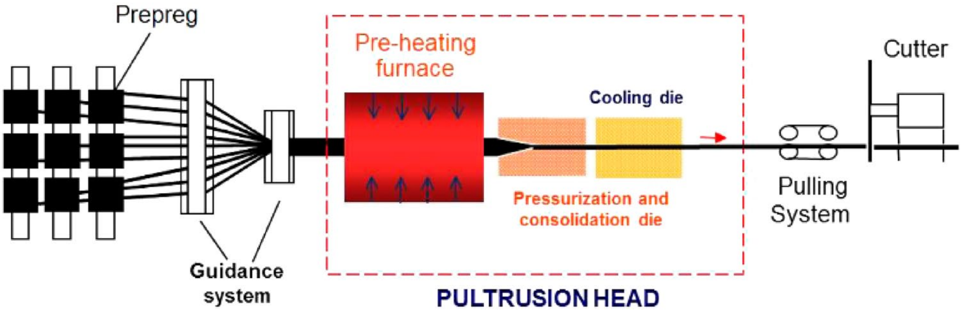


Fig. 5 Thermoplastic pultrusion equipment, reproduced from [51] under open access license

4 Post-processing machining operations

Components of aeronautical structures are generally assembled using fasteners (rivets or screws) introduced into holes made using a drilling process. The number of holes needed for an aircraft structure is very high and can vary from several hundred thousand to several million, depending on the size of the aircraft [52–62]. As an example, on the AIRBUS A380 and FALCON DASSAULT F7X, the number of holes to be made are approximately 2,000,000 and 20,000, respectively, with a distribution of approximately 70% of them in the aluminum structure, 25% in the composite structure, and the remaining 5%, in the titanium structure [63]. Consequently, hole drilling is becoming the most required machining operation in the aeronautical industry.

On the other hand, edge trimming of composite parts is the primary and mandatory process used to remove excess materials after the demolding operation to achieve final dimensional specifications [64–67]. In other words, edge trimming must also be carried out to remove the non-compliant and non-homogeneous edges of the parts (Fig. 6). Thus, shapes and dimensions in line with the needs defined by the specifications can be obtained. Surface machining is also an important operation when preparing surfaces for bonding assembly for multi-material applications. This operation can be carried out in several ways, including conventional machining (removal by cutting tool

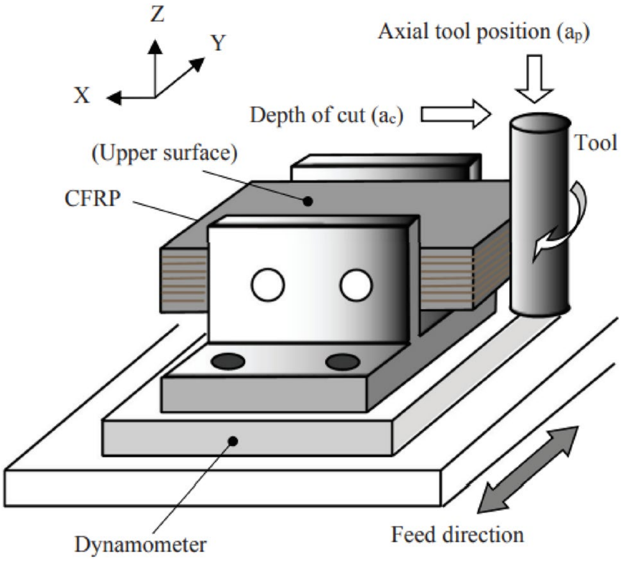


Fig. 6 Schematic of experimental apparatus for trimming by end mill, reproduced from [71] under open access license

or by diamond saw), and unconventional machining, using a high-pressure abrasive water jet (removal of material by erosion), for example. The heterogeneity and the anisotropy of composite materials affect their machinability compared to that of homogeneous and isotropic materials. Moreover, regardless of the machining process used (conventional or unconventional), the phenomenon of material removal is accompanied by different nature types of damage. With the appearance of this damage, compliance with the industrial criteria for machining quality (often those of homogeneous materials) becomes a difficult or even impossible task.

However, trimming and drilling of composite materials have been very challenging and difficult for the modern manufacturing community [55, 64–70]. Despite the specificities related to the machining of composite materials, the continuous improvement of their properties today requires mastering their machining techniques and improving their performance.

5 Machining carbon fiber reinforced polymer composites

When assembling composite structures, it is often necessary to use finishing operations. These are material removal operations performed using cutting tools. It should be noted that the machining of composite materials and CFRP in particular is different from that of metallic materials. This is mainly due to the abrasive nature of the reinforcements and the heterogeneity of composite structures. Indeed, during the machining operation, damage, such as the breakage of the matrix, burr, cavity, fiber fracture, the tearing of the fibers and the fiber/matrix delamination, is generated in the machined part [72–74]. To avoid or limit this damage, machining processes are often adapted to composites. The heterogeneity and abrasive nature of carbon fibers make the machinability of CFRP composites is more difficult than for conventional metal alloys. Thus, the machining of composite materials is presently considered a real challenge for industry and researchers.

Research into machining of composite materials has been undertaken since the early 1970s. Some pioneering research in this area started with the study of the machining of plastics [75]. The first theoretical study on the orthogonal machining of composite materials reinforced with strong fibers was presented by Everstine and Rogers [76]. Their study was strongly based on previous works such as Palmer and Oxley [77] and Pipkin and Rogers [78, 79]. Furthermore, they applied the theory of large plane deformations developed by Pipkin and Rogers [79] to the problem of orthogonal cutting, in which the leading edge of the tool is perpendicular to the direction of relative motion between the tool and the workpiece. By taking account of the material properties, the tool geometry and the proposed deformation, a tentative estimate of the forces required to maintain continuous machining was derived. Unfortunately, their work lacked experimental verification. Subsequent papers discussed the peculiarities of machining composites [80–82].

A few years later (1980), Koplev et al. [83] carried out the first experimental works on orthogonal cutting of UD-CFRP composites. Their work is deemed to represent one of the first real attempts to understand the machining behavior of fiber-reinforced composites. They found that composites have a different cutting mechanism from that of metals, and that the removal of FRP is characterized by serial material fractures. In addition, a subsequent work (1983) by Koplev et al. [84] studied the relationship between cutting forces, the chip formation mechanism and the tool geometry during the orthogonal cutting of CFRP, for two fiber orientations: perpendicular (90°) and parallel (0°). They found that for 0° fiber orientations, a surface with visible fibers was produced. They also observed that almost all the fibers are fractured perpendicular to their longitudinal direction. However, for 90° fiber orientations, they found that visible fibers are no longer present on the surface. Furthermore, they concluded that the surfaces obtained when cutting parallel to the fibers are better compared to the ones obtained when cutting perpendicular to the fibers. The surface roughness quality is highly influenced by the cutting conditions and tool geometry, and so, the geometry of cutting tools must therefore be optimized to improve the cutting mechanics and machinability in trimming and milling.

5.1 Machinability of CFRP in turning process

In the same year (1983), SAKUMA et al. [85] examined the effect of tool materials and cutting speed on tool wear during turning of CFRP pipes based on epoxy resin. Their findings were then compared with the data in a previous work dealing with GFRP. They found that both materials behave differently in terms of tool wear. They also found that the cutting speed has only a small effect on the wear rate. Unlike GFRP, the thermal conductivity was found to have a small impact on the performance of tools during CFRP turning. Their work was later accepted and published (1985) [85].

The machinability of CFRP during the turning process using an uncoated tungsten carbide tool (K10) was studied by Kim et al. [86]. The flank wear, the Taylor tool-wear constants, the surface roughness and the chip formation mechanism were experimentally investigated in their study. The optimum cutting conditions were then suggested. They found that the surface roughness is less dependent on the cutting speed as compared to the feed rate and the fiber winding angle. Similarly, Santhanakrishnan et al. [87] performed face-turning tests on CFRP composites using P30 and K20 sintered carbide tools. To evaluate the performance of each cutting tool used in their tests, the three components of the cutting forces were measured using a Kistler dynamometer. The influence of cutting conditions on the surface quality was also investigated in their study. They concluded that when turning CFRP, a K-type carbide tool performs better than a P-type one. However, the critical velocity was 100 m/min for both tools.

Other CFRP composite turning experiments were carried out by Ferreira [88] using several tool materials such as ceramics, polycrystalline diamond (PCD), cubic boron nitride (CBN) and coated and uncoated cemented carbides. They concluded that diamond tools are best for finish CFRP turning. Similarly, three types of cutting tool inserts, namely, ceramics, cubic boron nitride (CBN) and tungsten carbide, were tested by Rahman et al. [89] to machine long fiber and short fiber CFRP specimens in the turning process. Based on the cutting force, tool wear and surface roughness results, the authors concluded that CBN inserts represent a viable option when turning CFRP composite.

Furthermore, according to the CFRP turning experiments conducted by Belmonte et al. [90], the CVD coated Si3N4 cutting tool was found to better suited than the uncoated Si3N4 cutting tool. Rajasekaran et al. [91] conducted turning experiments on CFRP composites using a ceramic cutting tool. The optimal cutting conditions providing the best surface roughness were identified in their study using Taguchi's orthogonal array. They found that CFRP composites can be satisfactory turned using a ceramic tool. They also found that a lower feed value accompanied by a higher cutting speed represents the best combination offering the desired surface roughness. The same authors carried out turning experiments on CFRP composites using cubic boron nitride (CBN) cutting tools [92] and polycrystalline diamond (PCD) tool inserts [93]. The optimal cutting conditions were defined and the fuzzy modeling approach was used to predict the surface roughness [92] and the cutting forces [93] in their studies. They concluded that the fuzzy logic modeling approach can be successfully used for the prediction of the surface roughness and cutting forces.

In another study, Rajasekaran et al. [94] used Taguchi's orthogonal array in planning their experiment and the fuzzy logic modeling technique to predict the machining force and the specific cutting pressure during turning of CFRP composites with a K15 cemented carbide tool.

Sreejith et al. [95] studied the machinability of carbon/phenolic ablative composites using titanium nitride coated carbide and polycrystalline diamond (PCD) tools. The cutting force, the tool wear and the temperature were measured during face-turning under different cutting conditions. They found that during machining with the PCD tool, the temperature depends mainly on the cutting velocity, while in the case of the TIN-coated tools, it depends on both the feed rate and the cutting velocity. The temperature at the tool tip surface during turning of CFRP composites was also investigated experimentally by Chang et al. [96, 97]. They claimed that finite element analysis (FEA) can successfully be used for modeling and predicting the tip surface temperature. More recently, Sauer et al. [98] presented an experimental study on turning and orthogonal turn-milling of CFRP. They confirmed that in some cases, Hertel et al.'s model [99] can be used to calculate the force and the torque. However, it does not describe the anisotropy of CFRP composites. Demir

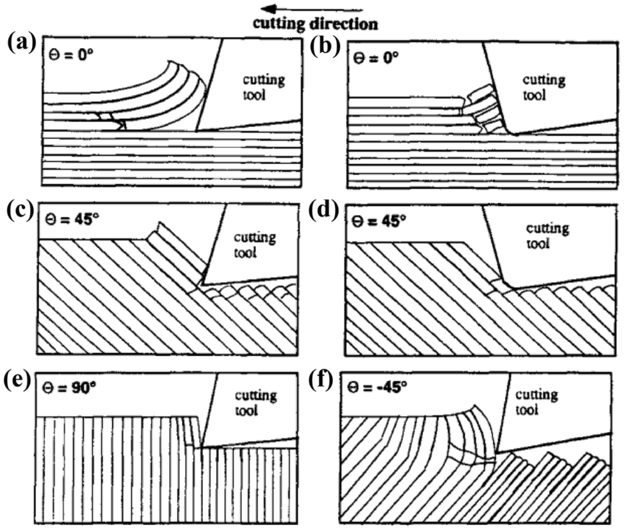


Fig. 7 Schematic description of the cutting mechanisms in the orthogonal machining of Gr/Ep: (**a**) delamination; (**b**) fiber buckling; (**c** and **d**) fiber cutting; (**e**) deformation; (**f**) shearing, reproduced from [117] under open access license

et al. [100] studied the machinability of CFRP composites during turning at different approaching angle and cutting conditions. They found that the feed rate is the most significant parameter followed by the approaching angle. The effect of the spindle speed was found to be less significant. Roy et al. [101] conducted high speed machining of CFRP epoxy on a lathe machine. The cutting force was measured and analyzed in their study.

It is worth mentioning that high speed steel (HSS) and plain carbide cutting tools are not recommended for machining fibrous composite materials. They are uneconomical and result in high tool wear and poor surface quality [84, 102, 103].

The optimization of the cutting process during turning of CFRP has been studied by several researchers using various approaches [104–109]. More recently, Abdur Rob and Srivastava [110] carried out turning experiments on CFRP composites using coated and uncoated carbide inserts. Furthermore, the optimal cutting conditions were determined based on Taguchi analysis, regression analysis and the Multi-Objective Genetic Algorithm. They found that the feed rate and cutting speed have the most significant effect on the tool wear for both coated and uncoated carbide inserts. They also found that a lower surface roughness and tool wear can be achieved using coated carbide inserts, while a lower cutting force can be obtained with uncoated carbide inserts.

5.2 Machinability of CFRP in milling and trimming process

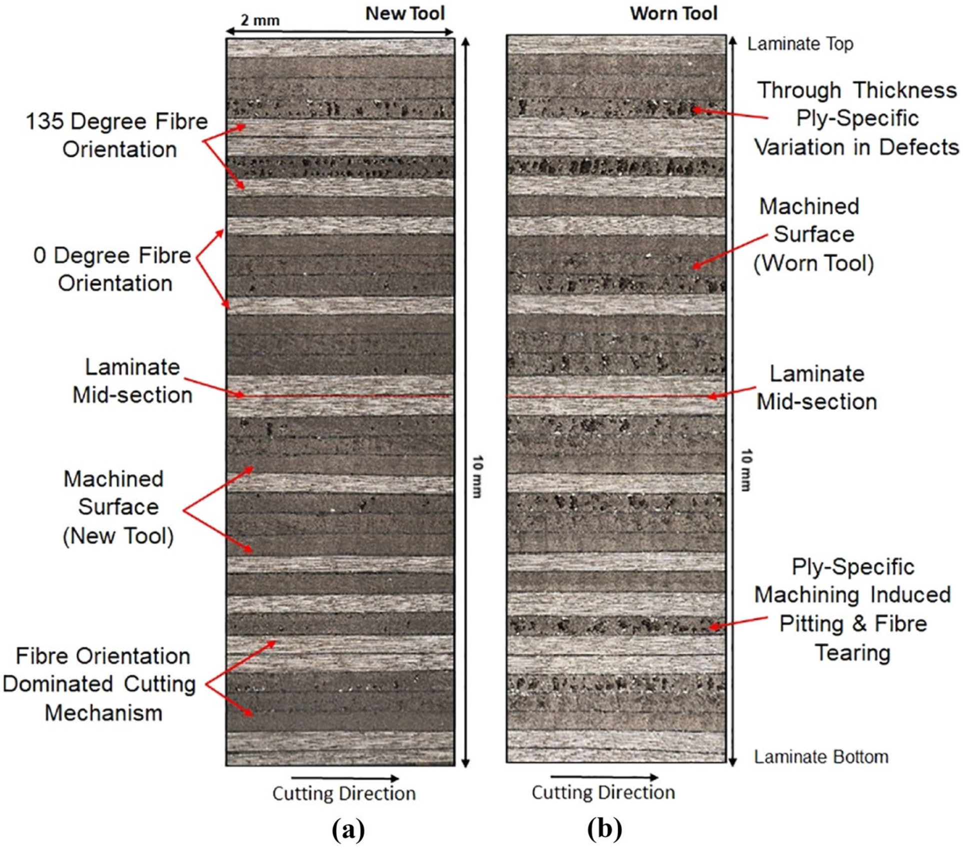
Milling and trimming composite laminates can cause surface delamination and lead to costly part rejection. It is therefore important to understand the factors that are most influential on the occurrence of surface delamination. Slamani and Chatelain [111] proposed three models, namely, kriging, Bezier and regression, for modeling the cutting force and surface roughness during high speed trimming of CFRP. They found the Bezier model to be the best suited in the context. Slamani et al. [112] presented two models (exponential model and multiplicative statistical model) to predict the cutting force and tool wear during high speed trimming of CFRP. Their results showed the exponential model to be more accurate.

Several experimental studies have demonstrated that the orientation of the fibers of a unidirectional ply with respect to the trimmed surface strongly influences the fiber breakage and delamination mechanisms [113–118]. According to Ramulu [117] the cutting mechanisms present in machining of FRP materials are frequently accompanied by delamination, fiber buckling, fiber cutting, deformation and shearing. Figure 7 provides a schematic description of this cutting mechanism.

The fiber orientation is also found to be the most important parameter affecting the tool wear, and hence, the surface integrity, during the machining of CFRP composites [119–123]. The – 45° ply orientation for machined CFRP specimens is associated with a poor surface roughness and high surface damage, which are likely due to the bending of the fibers during machining [65, 124]. Furthermore, pitting defects and torn fibers are predominantly observed for the – 45° fiber orientation plies (Fig. 8) [125].

The occurrence of delamination is also influenced by the tool geometry, via the dimensions of the nose radius and the helix angle, for example [113, 114, 126, 127]. Tool wear leads to changes in tool geometry such as an increased nose radius, which in turn influence the cutting force and temperature, and thus affect and alter the surface integrity

Fig. 8 Optical surface scan of machined surface: (**a**) new cutting tool and (**b**) worn cutting tool, reproduced from [125] under open access license



and delamination [65, 85, 114, 128–130]. PCD tools provide high wear resistance and low friction characteristics compared to other materials used to trim CFRP laminates [131]. Inoue et Hagino [129] carried out trimming tests on a quasi-isotropic carbon/epoxy laminate using five types of cutting tools: Poly-Crystalline Diamond (PCD), Tungsten-Carbide, HSS, Nitride HSS and TiAlN-Coated Tungsten carbide. They stopped their tests when a 0.2 mm wear was observed on the relief surface on the tool or when 30 m of trimming was reached. They found that the zero helix angle PCD tool was the most wear resistant and generated the lowest delamination and cutting forces. An et al. [132] conducted orthogonal machining on CFRP composites using five cutting tools with different rake and clearance angles. They found that the best tool performance is associated with large rake angles.

Besides the influence of the ply orientation and the geometry of the tool, the feed rate is the most influential factor in the delamination and the roughness of the contoured surface [133].

Bi et al. [134] conducted theoretical and CFRP machining experimental work using multi-tooth milling cutters with a segmented right-hand helical cutting edge (SRHCE) and segmented left-hand helical cutting edge (SLHCE). They found the SLHCE tool to be more wear-resistant than the SRHCE tool. They found also that a lower feed per tooth leads to high tool wear and poor surface quality.

Haddad et al. [64] reported that a multi-tooth cutter causes less damage when milling CFRP and decreases cutting forces, as stated by Chatelain and Zaghbani [135]. The normal cutting force was found higher than the feed force when trimming CFRP [136].

Several research works indicate that the most frequently encountered behaviors when machining CFRP are abrasion, fracture and chipping due to thermal and mechanical loads [85–87, 137]. Furthermore, crack propagation, delamination and fiber fracture can also be observed, as shown in Figs. 9 and 10.

Machining by chip removal of carbon fiber composites actually results in the creation of powder, and not the formation of a chip [84, 139, 140]. These powders are often propelled into the air around the cutting tool before falling and can then be inhaled by operators. Furthermore, these dusts are messy and harmful, which poses a major risk to the operator (causing toxic irritation), machine tool, and controls [141–143].

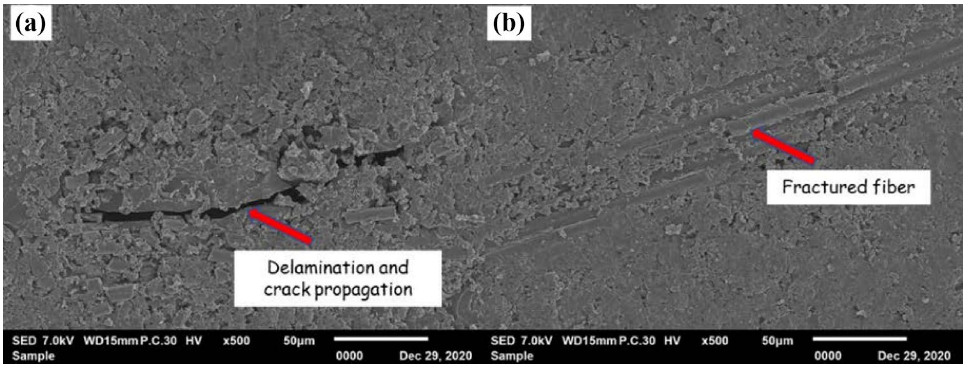


Fig. 9 Defects observed in SEM microscope during milling CFRP: **a** delamination and crack propagation and **b** fractured fiber, reproduced from [138] under open access license

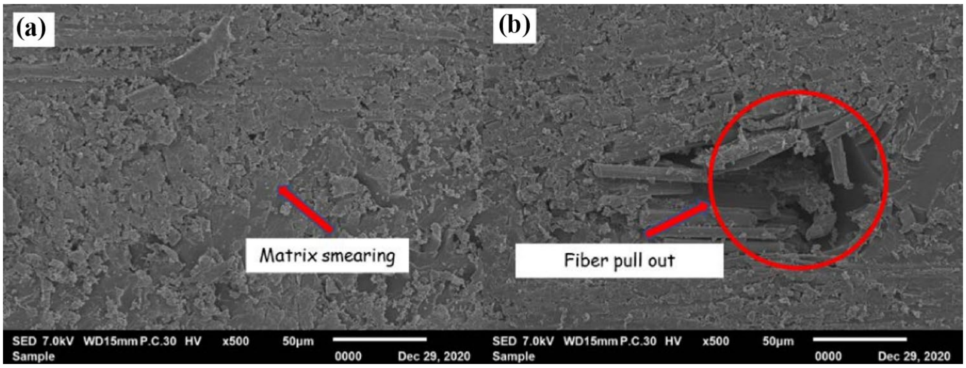


Fig. 10 Defects observed in SEM microscope during milling CFRP: **a** Matrix smearing and **b** fiber pull out, reproduced from [138] under open access license

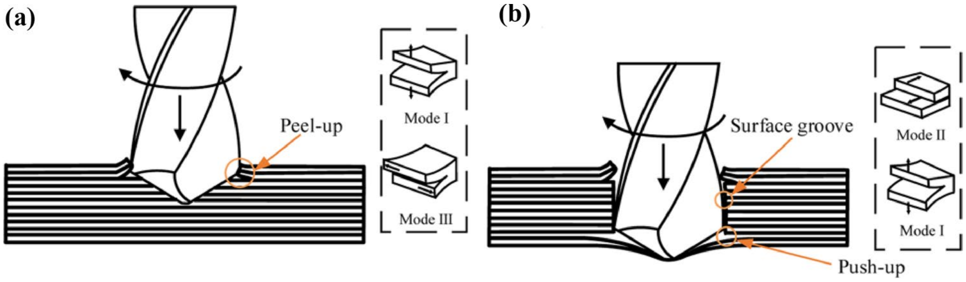
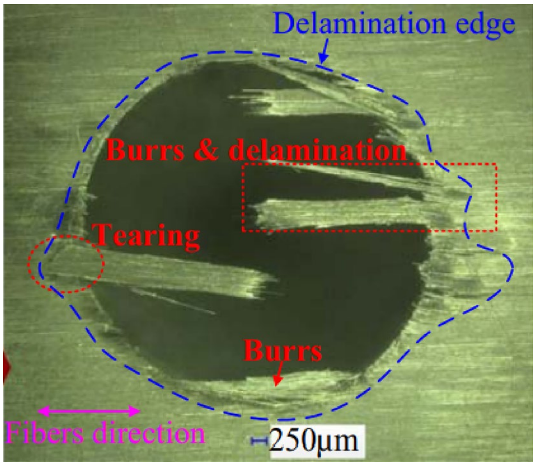


Fig. 11 Damage mechanism during drilling: (**a**) peel-up delamination, (**b**) push-out delamination, reproduced from [186] under open access license

5.3 Machinability of CFRP in drilling process

Damages such as peel-up delamination [144, 145], push-down delamination [146, 147], uncut fibers and fiber pull-out [148–151], tearing [152, 153], borehole damage [154–157], surface cavities [158–160], burrs [114, 149, 161], glass transition due to thermal damage of CFRP matrix [162–164] and sub-surface damage [67, 158, 165, 166] are key issues responsible for a large proportion of part rejections when drilling CFRPs (Figs. 11 and 12). They not only reduce the surface finish, but also affect the strength of the drilled holes [167–170]. Furthermore, many research works have concluded that the fiber orientation angle is one of the most important parameters at the root of damage occurrence when cutting CFRPs, particularly UD [171–174]. On the other hand, the cutting direction can also influence the damage distribution during drilling of CFRPs [175–177]. Çelik et al. [178] reported that the cutting force is more affected by the feed rate than the cutting velocity when drilling CFRP. However a high cutting force may lead to high-level damage, such as delamination and poor surface integrity [179]. The relationships between delamination, machining parameters and cutting force have been discussed in many research works [180–182]. These works concluded that the delamination damage increases with an increase of the feed rate. The effect of the cutting speed is less significant, as has been reported in other works [183–185].

Fig. 12 Delamination damage during the drilling of UD-CFRP, reproduced from [187] under open access license



6 Machining glass fiber reinforced polymer composites

The use of fiberglass dates back to the time of the ancient Egyptians, who used fiber glass to form their containers [188]. The first industrial applications of continuous glass fibers date back to the 1930s, and had to do with the electrical field characterized by high temperatures [188]. The functional characteristics of GFRPs are of the order of those of steels, while their rigidity is greater than that of aluminum alloys, and their density is a quarter that of steel alloys [189]. GFRPs benefit from excellent mechanical properties, good resistance to environmental factors, good impact resistance, relatively low density and good fatigue resistance [190].

Glass fiber composites occupy 95% of the international composites market [191], and are used in the majority of industrial fields. The automotive field is the first target of GFRPs thanks to their extremely interesting mechanical properties and their relatively low price as compared to carbon fiber composites. The construction field comes second, accounting for 26% of all GFRP usage [191].

Glass fibers have an excellent performance/price ratio placing them way ahead of other reinforcements currently used in the production of composite structures. Unlike natural fibers, glass fibers are characterized by good adhesion to all types of resins and good temperature resistance. They also have a low coefficient of thermal expansion. As well, they have the advantage of being inert and insensitive to the absorption of moisture.

6.1 Machinability of GFRP in turning, milling and trimming process

In 1988, Takeyama and Iijima [192] evaluated the machinability of glass fiber reinforced plastics/epoxy resin in orthogonal cutting with different fiber orientations. A method was proposed to estimate the average cutting force and roughness with respect to the fiber angles. Furthermore, a comparative experimental study was conducted between ordinary machining and ultrasonic machining. They found that ultrasonic machining leads to improvements of the burr, subsurface damage and cutting force reduction, and the enhancement of the surface roughness.

The optimization of cutting parameters when machining GFRP has been the subject of several research works [193–200]. Palanikumar and Davim [201] developed a regression model to predict the tool wear during GFRP machining. The effect of the cutting condition on tool wear was analyzed based on ANOVA. In another study, Palanikumar et al. [202] applied the Taguchi technique with fuzzy logic to optimize the machining parameters during GFRP composites turning using a carbide (K10) cutting tool. They claimed that their approach is more convenient and cost-effective in predicting the optimal machining parameters.

Ducobu et al. [203] conducted a comparative analysis of the performance of three cutting tools with different geometries during milling of GFRP composites. The comparison was performed in terms of delamination and cutting force. They found that a two-tooth PCD tool with a straight edge inclined provides the best performance and a lower cost. Prasanth et al. [204] conducted end mill experiments under different spindle speeds, a constant feed rate and a constant depth of cut, using five carbide cutting tools with different rake and clearance angles. They found that a

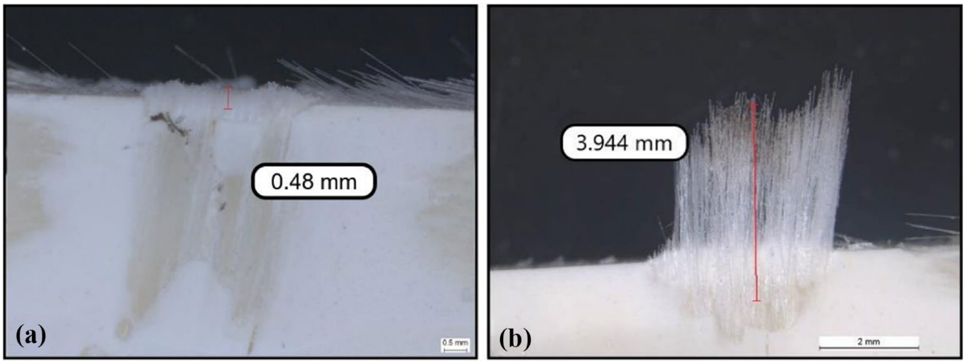


Fig. 13 Microscopic image of delamination after milling GFRP composite: **a** type I delamination, **b** type I/II delamination, reproduced from [203] under open access license

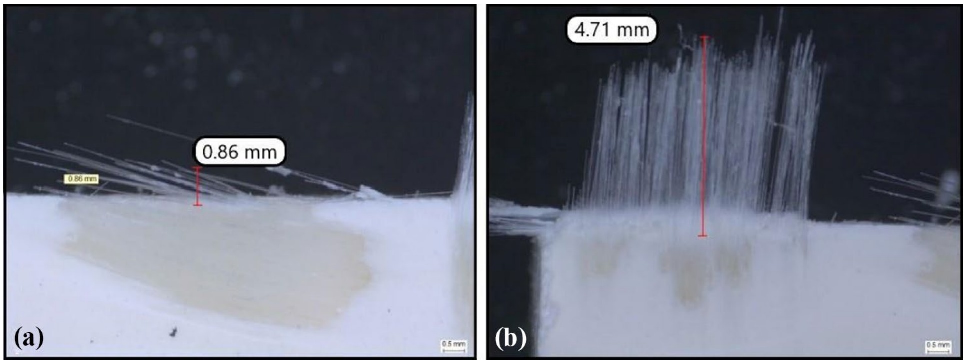


Fig. 14 Microscopic image of delamination after milling GFRP composite: **a** type III delamination, **b** type II delamination, reproduced from [203] under open access license

cutting tool with high rake and clearance angles is recommended for machining GFRP. Davim [205] studied the influence of cutting parameters such as the cutting velocity (v_c) and the feed rate (*f*) on the cutting forces, delamination factor (F_d), surface roughness (R_a) and the dimensional accuracy, when trimming 65% fiberglass and unsaturated polyester matrix composites. Their experiments were performed using a tool with 5 mm-diameter brazed carbide inserts (K10). As a result, the cutting forces, the dimensional accuracy and the roughness increased with the feed and decreased with the cutting speed. The delamination, on the other hand, increased as much with *f* as with v_c.

According to Jenarthanan and Naresh [206], the feed is the parameter with the greatest influence on delamination, followed by the cutting speed and the depth of cut, when trimming bi-directional GFRPs. A plausible explanation for this phenomenon is given by Davim et al. (2004), who reported that an increase in *f* leads to an intensification of heat generation, and therefore, to an initiation of tool wear, which generates higher roughness. Also, increasing *f* generates an increase of the feed force, which leads to more vibrations, and therefore, to more machining defects. Figures 13 and 14 show examples of different types of delamination on milled GFRP coupons taken with a microscope [203].

Azmi et al. [207] highlighted the difference between the quality of the surface finish generated by a worn tool when the cut is made in the longitudinal direction (0°) or the perpendicular direction (90°). They identified the constants of a Taylor model when trimming a glass/epoxy composite with an uncoated carbide brazed cutter. They noticed the appearance of uniform scratch marks on the flank face of the tested tool. These marks are caused by friction between the cutting tool and the abrasive fibers. They concluded that the cutting speed is the parameter that most influences the tool wear, followed by the fiber orientation. The feed rate, on the other hand, has a minimal influence on wear. Also, a longer lifetime can be achieved when the fiber orientation is equal to 90° compared to the lifetime when the orientation is equal to 0°. This is explained by the cutting mechanism: a cut in the orientation of the fibers (0°) generates bending and buckling of the fiber, and therefore, more fiber/tool friction, which initiates wear. Similar to what is stated above, tool wear is correlated with the cutting speed. They also concluded that there is a reciprocal influence between wear and cutting forces.

Tool wear is one of the major problems in composite machining. Indeed, it affects the quality of the machining, in terms of the surface finish and the productivity. Flank wear *Vb* caused by abrasion was found to be the most common wear in GFRP trimming [208]. This wear is defined according to the ISO 8688-2 standard (International Standard Organization, 1989). The life of a flank-worn cutting tool is limited to a *V*B of 0.3 mm, after which the tool is considered non-functional and must be changed.

In order to quantify the impact of this issue, a mathematical model of tool wear when turning a glass/epoxy GFRP as a function of cutting speed, feed, depth of cut and fiber orientation was developed by Palanikumar et al. [201]. The orientation of the fibers represents one of the main factors dictating the physical failure mechanism of the composite, and therefore, the intensity of the forces applied to the tool leading to its wear. Kharwar and Verma [209] proposed a hybrid module based on the Taguchi method and on Grey relational analysis embedded in an artificial neural network to optimize the cutting force, surface roughness and to rate the materials removal rate during turning of GFRP composites.

Yuanyushkin et al. [210] studied the trimming of a glass/phenol epoxy composite. They were particularly interested in the effect of the cutting tool and its wear on the arithmetic roughness. To this end, a modular cutter and 3 types of inserts carbide, namely, VK3M, VK15 and VK8, were tested. The authors concluded that there is an allowable limit for radial wear (350 µm), beyond which *Ra* exceeds 10 µm. It should also be noted that roughness is an increasing function of wear. However, this result is contradictory with the earlier statements by Hamedanianpour and Chatelain [128], who find that flank wear decreases the surface roughness (*Ra*) when trimming a quasi-isotropic carbon/epoxy laminate.

6.2 Machinability of GFRP in drilling process

Lin and Shen [211] studied the high speed drilling behavior of unidirectional (UD) fiberglass reinforced composites. The cutting speed range studied was between 210 and 850 m/min. Two types of tools were tested: a twist drill and a multi-face drill. They observed that the axial distance between the outer corner of the cutting edge and the tip of the drill increases with tool wear. This led the authors to propose a variation of the tip height (axial distance) as a wear quantification parameter for multi-facial (C-shaped) drills. This finding was also confirmed by Lin and Chen [212] in the case of composites drilled with carbon fiber reinforcement. They observed that the wear of tungsten carbide drills becomes quite substantial when the cutting speed increases.

In a study examining the drilling of a glass/epoxy composite, Tagliaferri et al. [213] underlined the absence of a standard for assessing the damage inherent to a cut. The authors quantified the spall damage by the damaged width marked by a penetrating liquid. They determined that the cutting speed-to-feed rate ratio (v_c/f) is a very influential criterion. Their findings show that for a v_c/f ratio of less than 100, drilling with a high speed steel drill with a diameter of 8 mm generates thick and irregular chips, and a v_c/f ratio greater than 250 gives chips in the form of dust (or powder). For very large values of the v_c/f ratio, the thermal damage to the fibers and the resin remains limited to a small volume around the hole. This work was extended by Di Ilio et al. [214] for drilling operations of a unidirectional thermoplastic composite reinforced with carbon fibers. They noted that the damage is influenced by the orientation of the fibers (low damage when the fibers are oriented from 0° to 45°).

To reduce damage on the entire periphery of the hole, Tagliaferri et al. [213] found a feed per revolution limit, which is the ratio of the feed rate to the rotational speed (function of the cutting speed and the diameter of the tool), of 0.3 mm/rev. The morphology of the piercing edges is unequal, depending on the orientation of the fibers. The inside of the hole is generally smooth, except in the case of large feeds.

A modeling and optimization approach based on response surface analysis and artificial neural networks was recently used by Abd-Elwahed [215] to predict the drilling process parameters and optimize the cutting conditions during drilling of woven glass fiber reinforced epoxy composite with different laminate thicknesses. They found that maximizing the drilling torque and minimizing the delamination factor requires drilling with a low feed rate and high spindle speed.

Mohan et al. [216] found that together, the thickness and drill size are the most significant factors affecting the torque. The cutting speed and drill size were the main factors affecting the cutting thrust. Erturk et al. [217] studied the effect of machining parameters on the drilling performances of GFRP composite. They found that the tribo-mechanical behavior of this process is influenced by tool coating. They also found that the drill bit type is the key parameter affecting the temperature of the material.

Tian et al. [218] studied the effect of the machining parameters and the clearance angles of outer cutting edges during drilling of GFRP composites using three candlestick drills. The delamination factor was analyzed using the response surface approach. They found that the damage at the hole exit is the result of the simultaneous combination of the cutting force, the thrust force and the drilling temperature. They specify that it is not recommended to drill at high speed when the clearance angle is relatively small. Using high speed increases the temperature at the hole exit, which in turn leads to failure of the resin and then increases the exit damage. On the other hand, Davim et al. [219] show that the Brad and Spur drills provide better performance in term of delamination and surface roughness than the Stub Length drill. Jessy et al. [220] studied the effect of various cooling conditions on the temperature of the drill bit and flank wear during drilling of GFRP on CNC lathe using a TiN/TiAlN coated drill. They found that an internal coolant is a very efficient technique leading to a 76% temperature reduction as compared to dry drilling and 66% as compared to the external coolant method. Furthermore, a reduction in flank wear and an increase in tool life were obtained thanks to a reduction of the tool temperature. Caprino and Tagliaferri [221] reported that during drilling of GFRP, the feed rate strongly affects the type of damage occurring. Inoue et al. [222] found that when drilling a high number of holes of GFRP with constant quality, a high feed rate is recommended. However, when high quality hole is required, a low feed rate is the preferred choice. They also found that for a small diameter drill, the ratio of the radius of the drill to the width of the yam is the key parameter in estimating the tool life.

Liu et al. [223] studied the effect of the cutting tool geometry on the delamination factor and thrust force during drilling of GFRP. A twist drill was compared in terms of thrust force and delamination with three candlestick drills with different tip geometries. They concluded that optimizing the geometric angles of the candlestick drill can significantly improve the peel-up and push-down delamination and reduce the thrust force. Palanikumar et al. [224] investigated the influence of the cutting parameters and drill geometry on delamination produced during drilling of GFRP composite. A response surface model was then used to predict the delamination factor. They found that the drill point angle has only a limited effect on the delamination factor.

To monitor the tool wear during machining of composite materials, the wavelet transform has been used by several researchers [226–231]. Velayudham et al. [232] studied the dynamics of drilling high volume fraction GFRP composites. They stated that their results prove the validity of the wavelet packet decomposition approach in signal characterization.

Several approaches, such as C-Scan [60, 233], the shop microscope [234, 235] and digital photography [236–240], have been developed and used to assess the delamination present after drilling FRP composites. The digital analysis approach was used by Davim et al. [241] to measure the adjusted delamination factor during drilling of GFRP. They concluded that their proposed approach is suitable for estimating the damage produced after drilling FRP.

When the composite is subjected to an axial force and pending during drilling, push-out delamination of the bottom surface occurs through both modes, I and II [225]. Figure 15 shows some illustrative example of peel-up and push-out delamination at different feeds, speeds, and laminate thicknesses [225].

7 Machining natural fiber reinforced polymer composites

Today, many industries, such those in the automotive sector, are gradually assuming their respective shares of responsibility in developing alternative manufacturing methods based on natural resources, all in a bid to situate their activities within the context of a more sustainable vision.

Glass or carbon fibers are widely used as composite reinforcements for structural or non-structural parts, and offer exceptional mechanical properties. However, these synthetic fibers consume a lot of energy to manufacture and are not biodegradable. Environmental degradation is close to the heart of the industries of today and tomorrow, especially when

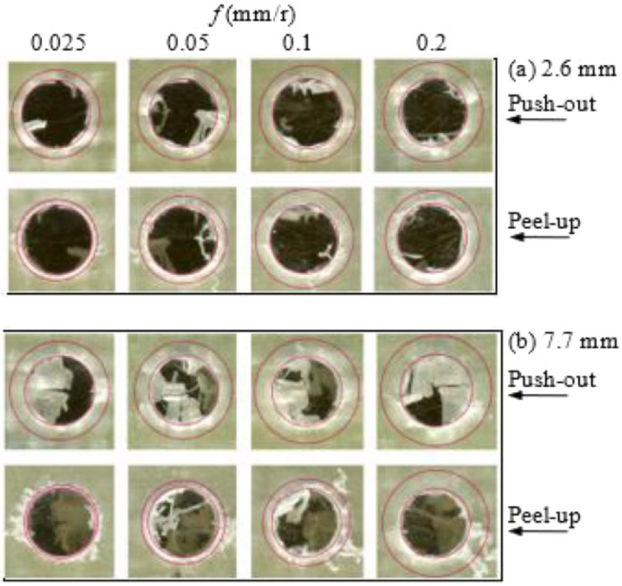


Fig. 15 Delamination in the drilling of GFRP laminate at different feed rates, reproduced from [225] under open access license

it comes to recycling end-of-life products. It is in this context that natural fibers have emerged in recent years. While they are certainly less resistant than carbon fibers, they do have the advantage of being lighter, with a specific resistance comparable to that of glass fibers. Moreover, they are present in large quantities, are relatively cheap, are biodegradable and recyclable, and need lower energy for their production, factors that all respond to ecological concerns [242–244]. In addition, unlike carbon and glass fibers, these fibers are non-abrasive.

Natural fibers and their composites find a wide range of applications, and can be found in recreational industries, among others, where elements such as ecological flax fiber kayaks or new generation tennis rackets can be seen. They are also of interest to the marine sector [245, 246] and the automotive industry for the production of non-structural parts such as door trims, trunk trims, rear shelves, seat backs or mirror shells [247–250]. Further, they are used in the construction of buildings, in packaging, in furniture manufacturing, and in shipbuilding, where items such as winches are being made from a polymer matrix and cotton fibers [251, 252]. The most widely used of these fibers are cotton, flax and hemp, sisal, jute, kenaf or coconut fibers [253, 254]. They offer excellent mechanical resistance and specific properties. Produced locally, they are available and their price is relatively low.

However, unlike glass or carbon fibers, natural fibers are not inert, but rather, are relatively sensitive to temperature and humidity, which explains why their use still lags behind that of synthetic materials [255, 256]. Hybridization of two or more different kinds of fibers in the same matrix is one of the promising approaches to minimize this effect and improve the properties of composite materials [257–260].

Avril et al. [261] confirm that regarding unidirectional traction, the best resistance is offered by unidirectional reinforcements, which is in agreement with the literature review presented by Teti [262]. In their paper, the authors attempt to identify the best bio-composite that can replace synthetic fibers for applications dedicated to the structure of automobiles. The composite sought had to have performances comparable to those of fiberglass composites and should be available on the European industrial market. They reported that the best candidates meeting these criteria are flax and hemp fibers. The availability of the latter as a semi-finished product ready to use being an issue, the flax fibers proved to be the most suitable reinforcements.

The machining of natural fiber composites differs significantly from that of metals. Several works have proven that the cutting behavior of natural fiber composites differs from that of synthetic fiber composites [263–269] due to the complex cellulosic structure of natural fibers [270]. The multiscale structure of NFRP makes their machining process more complex and requires a multiscale analysis to address their machinability from the microscopic scales of the fibers, which themselves constitute composite materials, to the mesoscopic scales of fiber bundles, thereafter, towards global macroscopic scales [270–274]. Indeed, the anisotropy of the multiscale mechanical behavior of an NFRP material will influence the state of the machined surface. Discriminating as well as correlating these effects will require both characterization of the machined surface at the appropriate scale and topographic measurements containing the appropriate scales. This will subsequently allow a breakdown of these scales to analyze them separately.

The theory and machining models associated with metals can therefore not be applied to composites. On the one hand, the behavior of the composites depends on the distribution and the dispersion of reinforcements in the matrix, and on the other hand, this distribution is random and inhomogeneous. A thorough investigation is therefore necessary to determine the optimal cutting conditions such as cutting speed, feed rate, orientation of fibers and the geometry of the cutting tool.

7.1 Machinability of NFRP in drilling process

Some works address the drilling operation of composites made with a polymer resin and reinforced with plant fibers, such as banana fibers [275, 276], sisal [275, 277], date palm fibers [278], roselle [275], hemp [279], bamboo [280], jute [281, 282] and coconut [283, 284], while other works compare the drilling of NFRP and fiberglass composites [285, 286]. In terms of the cutting tools, the most commonly used drill bits are standard twist drills either made of high speed steel (HSS) [275–277, 281, 284] or tungsten carbide [279, 283]. The tip angle of the drill is typically 118°. There are also other types of tools tested for drilling NFRP composites, such as the Brad-type drill for tungsten carbide [286] or a drill bit in HSS having 2 cutting edges [277]. In most of these studies, the diameter of the tools varies between 3 and 14 mm.

The selection of the machining parameters affects the drilling performance. The main drilling input parameters have often been the drill hole geometry and material, the tool diameter, the cutting speed, and the feed rate [287–290]. The analysis of variance (ANOVA) conducted in the above works show that the feed rate contributes the most to the evolution

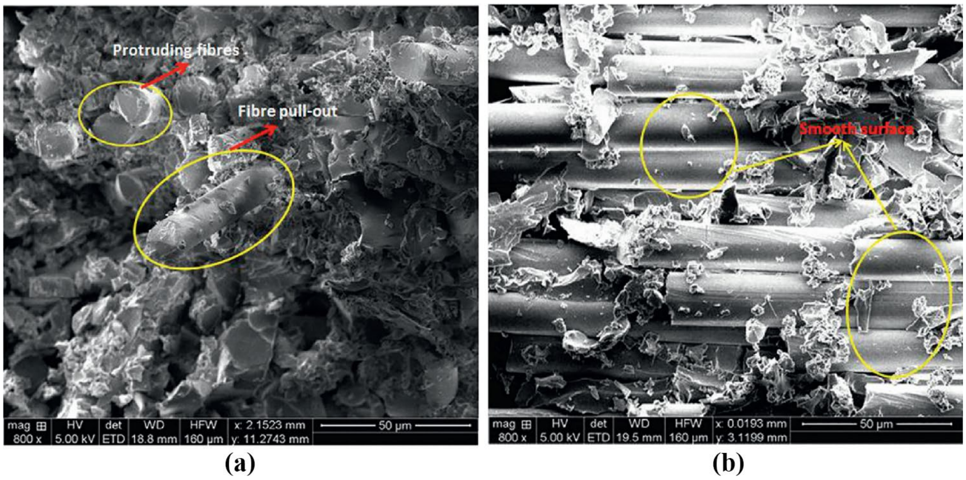


Fig. 16 SEM photographs of the inner surface of a drilled coir fiber-reinforced polyester composites hole: **a** protruding fibers and fiber pull-out, **b** smooth surface, reproduced from [291] under open access license

of the cutting forces and the delamination rate, followed by the diameter of the tool, and then, the cutting speed [275, 280]. The analytical models chosen to predict the rate of delamination as well as the cutting forces are multiple linear regressions with interaction effects.

Figure 16 shows the SEM photographs of the inner surface of a drilled coir fiber-reinforced polyester composites hole with maximum delamination [291]. A non-uniform wall surface and fiber pull-out due to the cutting action was observed (Fig. 16).

7.2 Machinability of NFRP in milling and trimming process

Regarding the NFRP milling process, much fewer works are available in the literature [66, 292–297]. A 4-tooth high speed steel (HSS) helical milling cutter with a 7 mm diameter was used by Vinayagamoorthy et al. [292] to groove jute fiber samples. Babu et al. [293] compared the machinability of 3 different unidirectional NFRPs (banana fiber/polyester (BFRP), hemp/polyester (HFRP) and jute/polyester (JFRP)) with a glass/polyester composite (GFRP) for the trimming operation. The aim was to evaluate the influence of the cutting speed and feed rate, at a constant cutting depth, on the delamination factor as well as on the roughness of the finished surface obtained by dry milling using a brazed carbide end mill. The results validate the literature presented by Teti [262]. They show that the delamination factor and the arithmetic roughness (Ra) of the finished part decrease with increasing cutting speed and increase with the feed rate. These two parameters exert the greatest influence on the delamination and surface roughness. Furthermore, the contribution of the feed rate is 2–3 times greater than that of the cutting speed. In the same context, Slamani et al. [66] conducted an experimental comparative evaluation of the machining quality of flax fiber (FFRP) and glass fiber reinforced polymer composite (GFRP) during the edge trimming process using two different cutting tools. They found that two-flute uncoated carbide end mills perform better with FFRP, while the two-flute polycrystalline diamond end mills are more suitable for trimming GFRP.

Delahaigue et al. [298] were interested in the trimming process of unidirectional and bidirectional flax fibers epoxy composites. They confirm the good machinability of this material. No tool wear was observed, which proves the non-abrasive character of flax fibers. Indeed, the lifetime of a classic diamond coated carbide tool is only a few meters for the machining of a carbon fiber composite, but it is much higher for a flax fiber composite, which is less abrasive for the tool. Thus, the cost of the tools would be reduced, which is not an insignificant consideration for an industrialist. However,

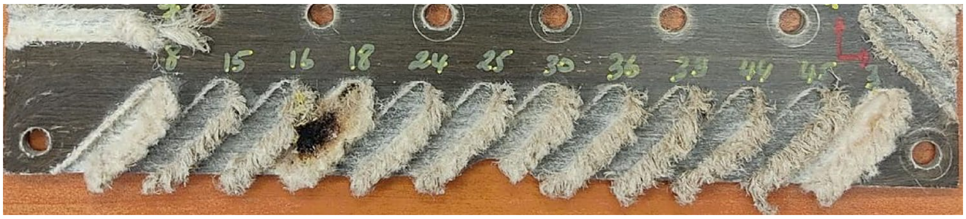


Fig.17 Burning of fibers during trimming FFRP, reproduced from [295] under open access license

due to the viscoelastic nature of flax fibers, trimming this material results in a poor surface finish, and ultimately, there would be a large number of uncut fibers and a high delamination factor. Furthermore, burning of the matrix and fibers can appear during the dry machining of NFRP under certain conditions [295]. This can be explained by the fact that when the feed is low and the cutting velocity is high, the temperature in the cutting zone increases, leading to machining-induced heat, which is the most common cause of burning (Fig. 17).

Merchant's model was applied by Chegdani et al. [299] to assess the effect of fiber orientation on the machinability of NFRP composites. They found that the orientation angle of fibers significantly affects the shearing and the friction energies. The 45° fiber orientation provides the best machinability, the 90° generates the highest cutting energy, while 0° induces the greatest surface roughness. They also found that the cutting behavior of the plant fibers and polymer matrix that constitute the composite materials is independent of the nature of the polymer matrix, i.e., thermoset or thermoplastic [300].

8 Conclusion

Composite materials such as GFRP, CFRP and NFRP are high performance materials. Thanks to their excellent properties and low weight, these materials are becoming very popular and widely used as compared to traditional materials. They are used in several applications and in different industrial production sectors. This explains the very active research that is ongoing in this field, and that is particularly devoted to the study of the machinability of these materials.

An extensive bibliographical review was carried out in this work in order to take stock of the behavior of these materials during cutting and to find the optimal cutting conditions for their machining.

Based on the comprehensive review of various research works, the following conclusions were drawn:

- An internal coolant is recommended when drilling FRP composites, as it leads to temperature reduction at the cutting zone, a reduction in flank wear, and an improvement in the tool life, surface roughness and delamination factor;
- High speed steel (HSS) and plain carbide cutting tools are not recommended for machining fibrous composites. A cutting tool with high rake and clearance angles is recommended for machining GFRP;
- The cutting behavior of natural fiber composites differs from that of synthetic fiber composites. The fiber orientation is the most important parameter affecting tool wear, surface integrity and delamination during machining of FRP composites;
- The feed rate has the greatest influence on delamination when trimming bi-directional GFRP composites. Increasing the feed rate leads to an increase in the feed force, which in turn causes more vibration, and therefore, more machining defects;
- The most commonly used drill bits for NFRP composites are standard twist drills made of high speed steel (HSS) and tungsten carbide. The drill bit type is the most important parameter affecting the temperature of the drilled material;
- Peel-up delamination, push-down delamination, uncut fibers, fiber pull-out, tearing, borehole damage, surface cavities, burrs, sub-surface damage, and glass transition are the most substantial types of damage occurring when drilling CFRPs;
- Delamination damage increases with an increase of the feed rate. The effect of the spindle speed is less significant. The occurrence of delamination is highly influenced by the tool geometry.

Author contributions MS: writing—original draft preparation. JFC: writing-reviewing. Both authors read and approved the final manuscript.

Declarations

Competing interests The authors declare no competing interests.

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