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A review on advanced cutting tools and technologies for edge trimming of carbon fibre reinforced polymer (CFRP) composites

Norbert Geier [a,*], Jinyang Xu [b,**], Dániel István Poór [a], Jan Hendrik Dege [c], J Paulo Davim [d]

[a] Budapest University of Technology and Economics, Faculty of Mechanical Engineering, Department of Manufacturing Science and Engineering, Budapest, 1111, Hungary
[b] Shanghai Jiao Tong University, School of Mechanical Engineering, State Key Laboratory of Mechanical System and Vibration, Shanghai, 200240, PR China
[c] Hamburg University of Technology, Institute of Production Management and -Technology (IPMT), 21073, Hamburg, Germany
[d] University of Aveiro, Department of Mechanical Engineering, Centre for Mechanical Engineering and Automation (TEMA), Campus Santiago, Aveiro, 3810-193, Portugal

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ABSTRACT

Recently, the use of carbon fibre reinforced polymer (CFRP) composites is predominant and will grow further. Although these fibrous composites are often manufactured near net shape, their mechanical machining is often required to meet dimensional tolerances. Considering the difficult-to-cut nature of CFRP composites, the technology planning of edge trimming of CFRPs poses significant challenges and obstacles. Therefore, the main aim of this study is to critically review and discuss challenges, recent expertise and experience gained in the area of edge trimming CFRPs. On the one hand, conventional and advanced edge trimming technologies are reviewed and compared. On the other hand, advanced cutting tools are presented and discussed. Finally, future scope and prospects are highlighted to determine further research scopes in the edge trimming of CFRP composites.

1. Introduction

Industries pose significant attention to the application of carbon fibre-reinforced polymer (CFRP) composites mainly due to their easy-to-shape nature and excellent material properties like high specific strength (*i.e.* high strength-to-weight ratio), excellent corrosion resistance, low thermal expansion, and thermal conductivity, high damping and good dimensional stability [1–4]. The application of these lightweight composites is beneficial in high-end industries to effectively reduce the operating weight of vehicles (*e.g.* aeroplanes, helicopters, spacecraft, cars, motorcycles, and ships) to achieve energy savings and emission reduction encouraged by society and policies. Furthermore, the CFRP applications are increasing in high value-added, lightweight and everyday consumer products, like sports equipment, medical devices, civil industries and construction [5–7].

Although CFRP composite structures have outstanding designability and are manufactured near net shape by automated and precise composite manufacturing operations (*e.g.* compression moulding, resin transfer moulding), mechanical machining of these composite parts is often needed to achieve the required dimensional tolerances and quality [8,9]. CFRP composite parts have higher strength and stiffness along the fibre direction(s); thus, CFRPs are inhomogeneous and anisotropic materials. The fibre direction and layup sequence are diversely designed in different fields of applications to match various mechanical requirements; however, these anisotropic properties of CFRPs pose a significant challenge in the technology planning of CFRP machining. Considering the direction-dependent material properties of CFRPs and the abrasive wear effect of carbon fibres on the cutting tools, CFRP composites are considered to be difficult-to-cut materials [4]. Implementation of improper technologies to machine CFRPs result in fibrous composite-specific geometric defects (*e.g.* machining-induced delamination, burr, fibre fragmentation, fibre pull-out, matrix degradation (*i.e.* cracking, smearing, and burning), fibre-matrix debonding) [10] and accelerated tool wear [4]. Therefore, proper planning of technologies and strict control of geometric damages is required to manufacture high-quality CFRP products and avoid time-consuming and costly post-machining or rejection of components [10].

Holes and edges are the most often required geometrical features in CFRP products [11], followed by other advanced features like pockets, slots and flat surfaces [12]. The challenges, technologies and solutions of

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* Corresponding author.
** Corresponding author.
E-mail addresses: geier.norbert@gpk.bme.hu (N. Geier), xujinyang@sjtu.edu.cn (J. Xu).

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hole-making in CFRPs are carefully reviewed and discussed in several publications [13–29]. However, the edge trimming of CFRPs has not been reviewed critically yet; this paper focuses therefore on the edge trimming of CFRPs. Edge trimming technology is applied to effectively remove the rest material left by the composite manufacturing process and to provide a suitable edge geometry having the required micro and macro geometrical properties. There are several possible technologies (*e.g.* conventional mechanical edge trimming, tilted mechanical edge trimming, ultrasonic vibration assisted mechanical edge trimming, curved circular cutting) that are capable of meeting these requirements; however, those significantly differ from the point of view of implementation ability, cost-effectiveness, programming difficulty, and material removal rates [9]. Conventional mechanical edge trimming is the most common technology having superior advantages like achieving excellent dimensional tolerances and easy industrial implementation [30]. However, when the cutting tool condition is not appropriate (*i.e.* tool is worn), the machined edges often consist of numerous trimming-induced burrs and delamination and resulting in CFRP part rejection. Researchers developed therefore advanced and non-conventional technologies to produce high-quality edges even by using an inappropriate conditioned tool. Researchers showed that the proper selection of the cutting tool (*e.g.* compression end mill having DLC coating with Zr–ZrN-(Zr,Cr,Al)N layers [31]) and technology (tool tilting [32,33] or vibrating [34,35]) could provide excellent quality edges in CFRPs. However, there are still unsolved challenges and a lack of knowledge and expertise in accurate edge trimming of CFRPs.

Considering that the expertise and experiences of the edge trimming of CFRPs are not reviewed yet, the main objective of the present paper is to critically review and discuss challenges and solutions of edge trimming of CFRP to support the correct selection and optimisation of machining strategy, cutting tool and process conditions. In addition, future trends and research directions are highlighted to support the research and development of the research community and industry.

This paper is structured as follows. First, the characteristics and challenges of edge trimming of CFRPs are presented in **Section 2**. Second, the most common and advanced edge trimming strategies are reviewed and discussed in **Section 3**. Then, the influences of the significant factors of the mechanical edge trimming strategy are overviewed in **Section 4**. Thereafter, **Section 5** provides an overview of special cutting tools capable of machining high-quality edges in CFRPs. Finally, lacks, challenges and future research directions are highlighted in **Section 6**. Although the most critical aspects of edge trimming of CFRPs are discussed in this paper (*i.e.* strategy, tool and parameters), the following additional issues – that are concerned but not focused on in this paper – are recommended to be dealt with in order to deeply understand advanced edge trimming of CFRPs: (i) chip removal mechanisms [36], (ii) delamination and burr formation mechanism [37], (iii) ultrasonic vibration assisted edge trimming [35], (iv) tool wear mechanism [38], (v) machine tools and industrial robotics [39], (vi) modelling of edge trimming [40], (vii) laser and water jet machining [41,42].

2. Characteristics and challenges of edge trimming of CFRPs

Key edge trimming technologies for CFRPs are categorised and illustrated in Fig. 1. Conventional mechanical edge trimming (also known and referenced as contour milling [43], side milling [44], edge routing, circular orthogonal milling [45]) is the most common edge trimming operation to machine high-quality edges in CFRPs. Considering the difficulties of conventional mechanical edge trimming (*i.e.* machining-induced burr and delamination), researchers developed the tilted edge trimming (also known as inclination milling [32]) technology to manipulate and control cutting force components that are responsible for machining-induced delamination and burr formation. The dominance of the cutting force components can also be manipulated by advanced cutting tools like compression end mills, as discussed in **Section 5**. On the other hand, ultrasonic vibration assisted machining (UAM) [35], abrasive water jet machining (AWJM) [42], laser beam machining (LBM) [41], electro discharge machining (EDM) [46],

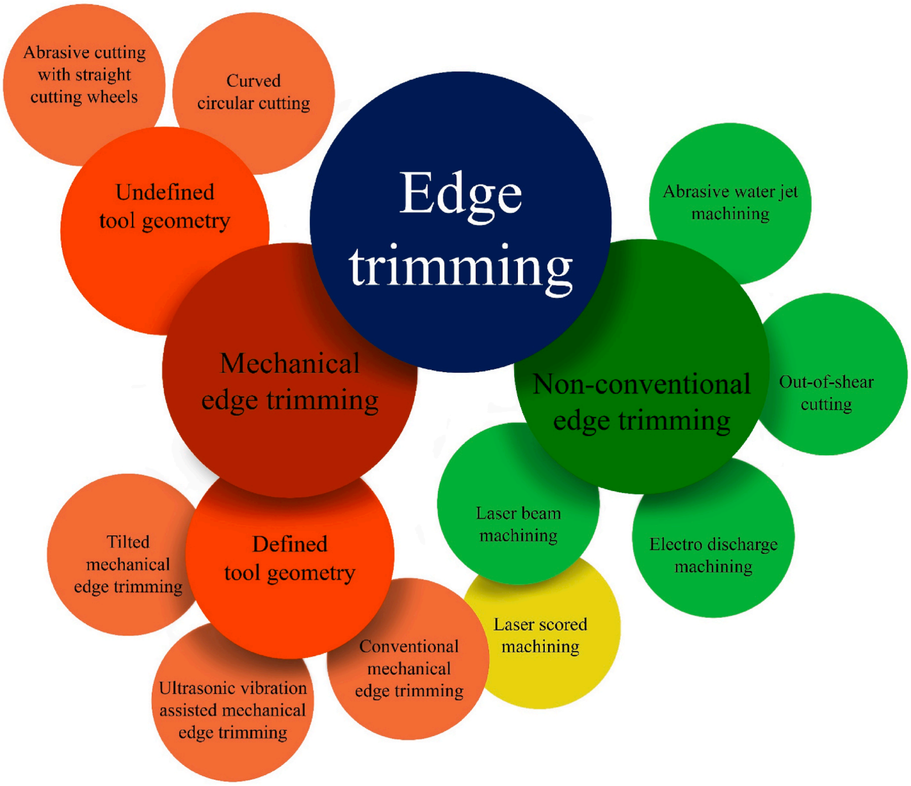


Fig. 1. Mind map of key edge trimming technologies capable of manufacturing sufficient edges in CFRPs.

out-of-shear cutting (OSC) [47] are also in the focus of interest, as each non-conventional and advanced technologies have considerable benefits in the edge preparation of CFRPs, as it is discussed in detail in **Section 3**. Considerable current research and development efforts are made on the suppression of edge trimming-induced geometric defects by using novel technologies, cutting tools and optimised parameters.

CFRPs pose significant challenges and difficulties in mechanical edge trimming. The following key issues are highlighted, which determine recent investigations and future works in edge trimming of CFRPs: (i) difficulty in avoiding machining-induced delamination and burr formation [48,49], (ii) a significant amount of dust-like chip generation [50], (iii) abrasive wear effect of carbon fibres on the cutting tool [4], (iv) often unknown rest material resulting in a difficult to consider fibre orientation, fibre content and width of cut (a_e) [51].

Edge trimming-induced burrs and delamination are the most severe defects that may significantly decrease the resultant strength and influence the initiation and propagation of failures [52]. Investigations of Freese et al. [53] showed that improper machining technology-resulted geometrical defects significantly reduced the strength of the CFRP adhesive joints. In addition, Chen et al. [54] highlighted that burrs and cracking damages degrade not only the assembly accuracy but also the load-bearing properties. Therefore, neither extended delamination nor significant burrs are accepted in CFRP applications. Since delaminated CFRPs directly break off the material continuity resulting in reduced resultant strength, delaminated CFRP parts are often directly rejected in the industry [55]. Although burrs can be removed later by several deburring technologies, these result in additional operational time and cost, making the CFRP applications more expensive and less sustainable [56]. It is essential to highlight that delamination and burrs are often formed simultaneously, making their inspection and control even more difficult. Both delamination and burrs are mainly formed at the top and bottom of CFRP plates, as these outer layers are not supported by other inner layers [57,58]. The manipulation of the cutting motion at the top and bottom of CFRPs is therefore a key issue, that is aimed to address by researchers using special cutting tools and technologies.

Chip formation of edge trimming of CFRPs is discontinuous and dust-like, regardless of machining parameters [52,59–61]. Considering that the size of these chips is 0.5 μm–8 μm [62], CFRP chips are suspended in the air, causing hazards that compromise operator safety and machine tool condition [61]. Despite some researchers, *e.g.* Nguyen-Dinh et al. [61] could reduce the dispersion of harmful chip particles in the air by increased feed and decreased cutting speed, it is still an important task to remove and filter remaining harmful particles from the air [63]. Chip removal is often solved by using industrial vacuum cleaners; however, positioning the target point of the tube of the vacuum device is challenging when edge large CFRP parts are trimmed.

The appropriate selection of cutting tool geometry is mandatory for high-quality machining of FRPs; however, tool wear results in changed tool geometry and modified chip removal quality. Therefore, the original tool condition should be kept as long as possible to ensure high-quality machining of CFRPs. Tool life can be increased by adequately selecting cutting tool material (*e.g.* solid carbide) and coatings (*e.g.* diamond), applying coolants to reduce friction and cutting temperature and optimising process parameters to reduce cutting force. Although the application of these solutions makes the tool life longer, their application suffers from some critical issues, like (i) the application of coatings increases the CER, thus changing dominant chip removal mechanisms, (ii) the application of coolants is often not adaptable (iii) multiple-objective optimisation (*e.g.* minimise tool wear and delamination and target the burr size), of process parameters is difficult. Kim et al. [64] conducted edge trimming experiments in CFRPs and found that the fibre orientation has a significant influence on the flank wear, as well as the speed of flank wear is faster at small cutting width applied (<1 mm). Therefore, the consideration of fibre direction and the proper selection of a_e is also recommended in the machining planning process to ensure high-quality machined features and sustainable tool condition.

Although the depth of cut (a_p) is equal to the CFRP plate thickness in the edge trimming technologies, the cutting width (also known as radial depth of cut – a_e) depends on the rest material, which is the result of the previous composite manufacturing technology. It is a considerable challenge that the fibre content and the fibre orientations in the rest material are difficult-to-plan, as it is significantly influenced by the applied composite manufacturing technology and its process parameters, material types and amounts. Therefore, the engineers either inspect the resulting rest material or consider the unknown size of the rest material using safety factors. The former solution is often supported by costly digital image processing technology, and the latter may increase the operation time and makes the process more challenging to control. The following sections of this paper present and discuss recent expertise and technologies in edge trimming of CFRPs considering the specific challenges discussed in this section.

3. Edge trimming technologies for CFRPs

The extremely high demand and necessity for edge trimming manufacturing operations for CFRP workpieces encourage a great variety of edge trimming technologies to be developed. Most edge trimming technologies originate from the experience of conventional mechanical cutting processes of metallic structures (such as side milling, profile milling or cutting with disc); therefore, the kinematics and the environment of these conventional machining technologies differ only slightly. However, because of the anisotropic nature of fibrous composite materials, there is a growing number of research for novel mechanical machining technologies and strategies (*e.g.* tilted edge trimming, curved circular cutting) aiming to control the acting cutting force besides process parameter optimisation. The other huge part of available technologies for edge trimming purposes consists of mainly laser beam cutting (LBC) and abrasive water jet cutting (AWJC), where the energy for material removal is transmitted directly to the CFRP material and not through a cutting tool. The available CFRP edge trimming technologies are schematically illustrated in Fig. 2, and their main advantages and disadvantages are summarised in Table 2. The detailed specialities, properties, benefits and drawbacks of the available CFRP edge trimming technologies are explained in **Subsections 3.1-3.5**.

3.1. *Conventional mechanical edge trimming*

Conventional mechanical edge trimming is illustrated in Fig. 2a and d. This technology requires only a conventional small helix end mill guided through an edge-parallel tool path which is easily programmed by available computer aided manufacturing (CAM) systems. Although a complex curved CFRP plate (*e.g.* Fig. 2d) requires more advanced programming skills and 4–5 axis machine tools or industrial robots to machine, a flat CFRP panel (Fig. 2a) can be finished by a 2.5-axis machine tool. In this technology, the axis of the cutting tool is always perpendicular to the tool path, which is beneficial from the point of view of implementation; however, it results in numerous challenges and difficulties in milling-induced defects such as delamination [2,58,65], burrs [33,43,66], inappropriate surface roughness [2,67] or matrix destructions (*e.g.* cracking, smearing, burning) [63,67]. Considering that the tool geometry (cutting edge radius, helix angle, rake angle, clearance angle *etc.*) has the most significant effect on the quality of machined edges [66,68], the appropriate selection of cutting tool is crucial. Researchers showed that the axial cutting force component is primarily responsible for machining-induced peel-up and push-out delamination formation [69]. Considering that this force component is primarily affected by the helix angle, compression end mills and straight-edge (*i.e.* helix angle of 0°) end mills are preferable by the industry [70]. The advanced cutting tool geometries are explained in detail in **Section 5**.

The applicability of conventional mechanical edge trimming technology is investigated through numerous experimental and analytical works. For example, Sheikh-Ahmad et al. [58] carried out conventional

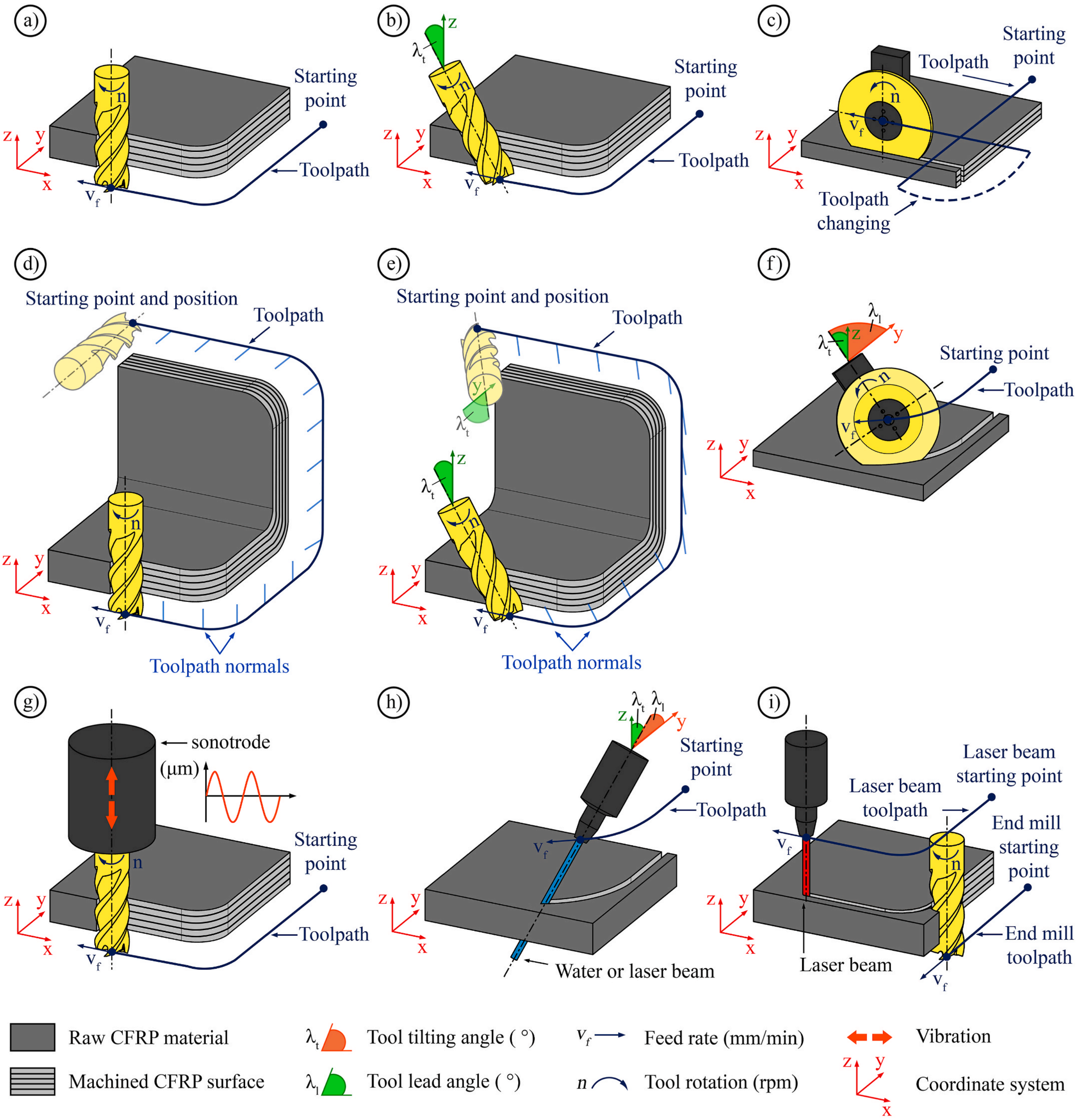


Fig. 2. Schematic illustration of edge trimming technologies of CFRP workpieces focusing on tool movements: a) conventional mechanical edge trimming, b) tilted mechanical edge trimming, c) abrasive cutting with straight grinding wheels, d) 5-axis conventional mechanical edge trimming, e) 5-axis tilted mechanical edge trimming, f) curved circular cutting technology, g) ultrasonic vibration assisted edge trimming, h) laser beam cutting or abrasive water jet cutting, i) laser scored edge trimming.

edge trimming experiments with burr tools (also known as router end mill [71] or compression end mill [72]) and measured the machining-induced delamination depth and the frequency of its occurrence in order to propose a new tool life criterion and evaluate an empirical tool life equitation. In their results, the delamination takes different forms (*i.e.* Type I-IV delamination), the delamination occurrence is statistical in nature, and the extent (*i.e.* delamination depth) follows a normal distribution. The feed rate was found to have the most significant effect on delamination, followed by cutting speed and tool wear, respectively. Slamani and Chatelain [65] investigated the capabilities of industrial robot trimming of CFRP parts through the effects of cutting parameters, robot position and machining strategy on the tool path deviation, cutting forces and cutting temperature. They also inspected the quality of the machined part by delamination, surface damage and deformity of the machined part. Their results show that the direction of machining significantly influences the path accuracy of the tool and the cutting temperature. They recommended that the feed rate and cutting velocity should be kept relatively low in order to minimise delamination. Hosokawa et al. [33] examined the effect of tool coatings and helix angle on surface integrity, cutting force and tool wear in the case of conventional edge trimming of CFRP. Their analysis of forces shows that the tangential and normal force components decrease with the increase of helix angle. However, they found that the extent of machining-induced burr (called 'fluffing') almost doubled in the case of a high helix angle ($\lambda = 60^\circ$) compared to the standard helix angle ($\lambda = 30^\circ$) as a result of the difference of the dominance of the axial cutting force. Cunningham et al. [2] examined the effect of a cryogenic environment in the case of conventional edge trimming of CFRP plates. The cryogenic cooling improved the surface roughness by 28.1 %. Furthermore, the up-down compression-type cutting tool produced less delamination (49.9 %) due to cryogenic cooling. However, in the case of the multi-tooth cutting tool, the effect of cryogenic cooling may be controversial due to the improved chipping mode tool failure. Slamani et al. [67] conducted conventional edge trimming experiments in order to investigate the effects of machining parameters on the surface roughness, surface damage, tool wear and cutting forces using a CVD diamond-coated carbide tool. They found that the surface quality improved with the increase of cutting length, which is an opposite tendency towards the priory information about the connection of tool wear and surface roughness. They explained it by the possibly occurring thermal deformation (such as matrix burning and smearing) of the composite, which smoothed the surface. Therefore, they proposed that the Ra surface indicator is inappropriate in such cases. They also stated that the delamination can be avoided by proper machining conditions, high fixture rigidity and good quality raw materials.

3.2. *Ultrasonic vibration assisted mechanical edge trimming*

Ultrasonic vibration assisted machining (UAM) technologies are improving conventional mechanical machining technologies (such as conventional edge trimming) by vibrating the cutting tool with a relatively high frequency and small amplitude [73,74]. The ultrasonic vibration assisted edge trimming technology is illustrated in Fig. 2g. In the case of ultrasonic vibration of the cutting tool, the contact time of the tool and workpiece decreases; therefore, the cutting forces and machining-induced defects can be reduced [10]. The vibrating motion of the tool can also significantly influence the tool's wear. Faster tool wear and the vibrating tool motion of the UAM technology can be disadvantageous on surface roughness [75]. The orientation of the tool compared to the machined surface also has a key role in the machined surface quality [34].

Szallies et al. [73] carried out low-frequency oscillated milling on CFRP composites and investigated the effects of vibration, tool and fibre orientation on delamination and surface roughness. They concluded that less delamination formed in the case of the oscillated solid carbide tool, independently of the fibre orientation. They also found that the oscillation of the tool did not improve the surface quality. Geng et al. [44] compared their proposed rotary ultrasonic elliptical machining to conventional grinding in the case of side milling of CFRP. The ultrasonic technology reduced the cutting forces by a maximum of 43 %. The surface integrity was also improved, while the conventional technology produced higher roughness and tool feed marks. Halim et al. [75] compared UAM and conventional milling technologies in CFRP composites experimentally. They observed faster tool wear in the case of UAM technology due to the increased friction of the tool and surface. The surface quality of the UAM was worse than the surface quality of conventional milling as a result of the vibrating motion of the tool. Wang et al. [34] examined the effect of tool orientation on cutting force, surface roughness and surface microstructure. Their experimental results show that using the tool side face in the case of UAM produces lower resultant forces; however, using the end face of the tool generates lower surface roughness and less microstructural damage (*i.e.* micro-cracking and matrix smearing). Although some results of researchers are promising when the ultrasonic vibration is applied; however, the difficulty of chip removal mechanics makes this process difficult to model and understand. Therefore, more sophisticated scientific works are needed in the future to describe the chip formation and surface generation mechanisms in UAM of CFRPs.

3.3. *Tilted mechanical edge trimming*

Tilted mechanical edge trimming (also called inclination milling [33]) technology is illustrated in Fig. 2b and e. Although this technology is not as spread among industrial practices as conventional edge trimming, it is a promising technology aiming to minimise machining-induced geometrical errors by controlling the effective angle between the helical flute of the end mill and CFRP composite. It is well known that the larger the helix angle, the larger the probability of delamination and burr formation is [33]. Therefore, researchers suggest tilting the helical cutting tool to provide more beneficial cutting mechanics [45]. The proper tilting angle is calculated from the helix angle; thus, the resultant cutting force directs parallel to the machined surface [33]. Despite the limited number of research about tilted edge trimming of edges of CFRP plates, many similar applications can be found which admit the advantages of tool tilting, such as tilted helical milling, wobble milling and tilted slot milling technologies [11,32,76–78]. Due to the basic principles of these advanced milling strategies, the acquired expertise can be adapted directly to edge trimming as well. Although the tilted technologies have complex programming demands (which can be easily compensated by CAM programming) and the required minimum number of machine tool axis (4 or 5 axes), the research and development of this technology may be crucial in the future.

Hosokawa et al. [33] proposed a novel edge trimming strategy called inclination milling, where the high helix angle tool is tilted in order to make the resultant cutting force direct parallel to the surface of the workpiece. They found that the tool wear was reduced significantly; also, the surface integrity was improved by the reduction of delamination and burrs. Pereszlai et al. [11] conducted machining experiments in CFRP with a tilted helical milling technology. Their results show that the tilting angle of the tool significantly influences the resultant force components and burrs. They found that the larger the tilting angle, the better the quality of the geometrical feature is; thus, the tilting angle is recommended to be maximised. Their kinematical analysis shows that the dominant force acts as pushing on the laminate layers instead of peeling up and separating the top layers due to the tilting of the tool. Considering that the hole milling strategies can be considered as specific edge trimming technologies, the findings of Pereszlai et al. could be adapted effectively to general edge trimming technologies. Schulze et al. [79] proposed first the wobble milling technology for better quality hole manufacturing in fibrous composites. They showed that in the case of wobble milling, the exit side damage was less than in the case of circular and spiral milling strategies. Pereszlai and Geier [78] investigated the positive effects of the wobble milling technology. They compared the hole qualities machined by wobble milling to the qualities of holes machined by conventional drilling and tilted helical milling. Their experimental results show that wobble milling produced the least amount of burrs in the case of each applied tool geometry. Furthermore, they could achieve IT8 quality holes in CFRPs by wobble milling. The highly advantageous effects of tilting the milling tool at wobble milling suggest that the tool tilting at edge trimming may also be beneficial; however, a significant effort is needed in the future for better explanation and optimisation of tilted mechanical edge trimming to support its spread in the industry.

3.4. *Abrasive cutting with straight grinding wheels and curved circular cutting*

Abrasive cutting with straight grinding wheels is usually used for cutting straight contours on large parts, as it is illustrated in Fig. 2c. The grinding wheel diameter normally exceeds the material thickness by far.

This leads to a beneficial ratio of cutting time to cooling time at the abrasive grains, which enables a low thermal load. This process is well suited for cutting brittle CFRPs with thermoset matrices and is often much more productive in comparison to trimming with end mills. For CFRP cutting galvanically bond, coarse-grained, mono-layer diamond grinding wheels with a metal body are mostly used to increase the heat flux into the tool and reduce the thermal load on the part. This enables dry-cutting processes [80]. Klingelhöller [81] showed that the grinding wheel temperature in dry machining of a carbon fibre epoxy composite might increase degressively from 130 °C to 290 °C while machining along fibre direction and from 300 °C to 440 °C, at transversal machining while increasing feed rate from 1.5 to 4.5 m/min at the point in time when thermal equilibrium is achieved, and the heat flow given off to the environment by convection is equal to the heat input via the separation process. Due to the small contact time between the CFRP workpiece and grinding tool, no thermal defects occur on the matrix. Temperature measurements close to the cutting zone when cutting thermoset-CFRP fabrics with an electroplated diamond grinding wheel show that the temperatures differ only slightly in the case of up or down-cutting [82]. Due to flat cutting edge trajectories and low single-grain cutting forces, the surface quality on the exit side of the grinding wheels usually is very good, with nearly no delamination [80].

To enable the advantages of cutting CFRP with grinding wheels for parts with variable convex and concave curvatures or processing curved contours, the curved circular cutting (CCC) technology can be used [83]. The curved circular technology is illustrated in Fig. 2f. Here, specially profiled grinding wheels and a spatial adaptation of tool rotation axis orientation enables curved cuts with grinding wheels. The achievable minimum contour-radii, as well as the part thickness, are limited. In curved circular cutting, the contact areas can be divided into the outer cone cutting, where the curved component contour is created by a surface line of the conical abrasive disk, and front edge cutting, where the material surface trimming is realized by means of the peripheral edge of a cutting disc (see Fig. 2f) [84,85]. The comparison between conventional edge trimming with straight grinding wheels and curved circular cutting with specially profiled grinding wheels shows a high quality of the cut surface on both sides, generally negligible shape deviation of the cut profile and low cutting forces for both methods, which makes it possible to use them for unstable shell components and clamping situations as well as machining systems with lower rigidity, such as, *e.g.* industrial robots [86].

3.5. *Laser beam and abrasive water jet cutting in edge preparation of CFRPs*

Laser beam cutting (LBC) and abrasive water jet cutting (AWJC) for edge trimming purposes are illustrated in Fig. 2h. In the case of these technologies, the energy for material removing is transmitted directly via the laser beam or the suspension (abrasive particles in the water) and not through a cutting tool. The most beneficial property of LBC and AWJC is the wear-free nature of the technology [87], which can lead to economical advantages. A key difference compared to the mechanical edge trimming technologies is that the LBC and AWJC technologies are almost independent of the fibre orientation; the machining-induced geometrical defects are formed by the streaks of the laser beam or water jet [88]. LBC and AWJC edge trimming technologies also provide huge flexibility in the cutting process of complex contoured workpieces. Multi-axial cutting processes can also be performed with special multi-axis LBC and AWJC machines or with robotic systems [89]. LBC edge trimming technologies are also advantageous from the perspective of cutting forces, while the forces during machining are negligible due to the nature of the technology; therefore, the probability of the formation of typical mechanical machining-induced geometrical errors is low. However, it is important to highlight that the thermal effect of the laser beam can negatively affect the quality of the machined feature due to the relatively low glass transition temperature (T_g) and degradation temperature (T_d) of polymer composites, which properties are accompanied by the low and anisotropic thermal conductivity of the matrix material [90–93]. Therefore, numerous researches aim to simulate and analyse the heat affected zone (HAZ) [94] and optimise the key laser cutting parameters (*i.e.* pulse energy, pulse frequency, gas pressure) to achieve better results [95]. The AWJC do not convey heat as the LBC does, but other machining-induced damages can appear due to the forces and abrasive cutting mechanisms, such as delamination [96,97], fibre pull-outs [98,99], bad surface quality [100,101] and particle embedment [98,102]. To maximise the quality of water-cut features, the process parameters (*i.e.* stand-off distance, jet pressure, impact angle and feed) are recommended to be optimised [103]. The necessary cutting fluid management (filtration) and the high equipment costs reduce the benefits of AWJC technology [104]. Although these non-conventional edge trimming technologies are beneficial in the manufacturing of smaller composite parts, their spread is not as common in the high-end industries such as aerospace and automobile industries due to the challenges of laser beam/water jet management on the opposite site of the large CFRP parts [105].

3.6. *Laser scored edge trimming*

Laser scored machining (LSM) combines laser beam cutting with mechanical edge trimming in order to improve edge quality compared to employing either one of the processes individually [106]. It is illustrated in Fig. 2i. In the first step, a laser ablation process is used to introduce a superficial kerf (with a depth of around 0.25 mm) into the workpiece surface along the contour of the edge to be trimmed. In the second step, mechanical edge trimming is performed. During mechanical trimming, the pre-scored kerf inhibits the occurrence of typical edge defects such as delamination and fibre protrusions [106]. This is due to the fact that the outer ply has already been pre-cut by the laser, which reduces machining-induced stresses at the edge. Moreover, the outer ply supports the adjacent laminate layers, thus further stabilizing the edge. The principle of (mechanical) pre-scoring of the workpiece surface for the purpose of preventing edge damage, which is also referred to as pre-cutting, is an established technique in sawing of wood or wood composites [107] and was shown to be also applicable to trimming of CFRP by Geis et al. [108]. It was demonstrated that laser ablation could be similarly employed to pre-process CFRP workpieces in order to prevent edge damage in mechanical drilling [109] and mechanical edge trimming [106]. Utilizing laser ablation for pre-scoring instead of a mechanical process has the advantage of being a wear-free and force-free proceeds that is relatively insensitive to variations of workpiece thickness and can be applied to arbitrary edge contours. In comparison to laser-only cutting, laser pre-scoring only introduces a very small amount of thermal energy into the material, which effectively reduces the size of the heat affected zone (HAZ) [106]. Due to the inhibition of delamination, LSM increases tool life and enables the usage of higher feed rates compared to conventional mechanical edge trimming. However, it is a comparatively complex process that requires an elaborate machining system.

4. Influences of process conditions of edge trimming

The influences of process conditions (*i.e.* tool geometry, fibre orientation, feed and cutting speed, depth of cut, milling strategy, and cooling) on the machining-induced geometrical defects, surface characteristics, chip removal, and cutting energetics are discussed in this section. Considering that the process conditions have a significant effect on the quality of machined edges and the cost of edge trimming [67], an in-depth understanding of them is essential for efficiency and sustainability. Table 1 summarizes decisive research papers dealing with the determination of influences of process conditions on the mechanical edge trimming process in CFRPs, and highlights research gaps that may require focus of further investigations. A review and discussion of the

Table 1
Decisive papers dealing with the determination of influences of process conditions on the mechanical edge trimming process in CFRPs (NA denotes not available).

Factors	Response parameters						
	Cutting force	Cutting temperature	Tool wear	Delamination	Burrs	Microstructure	Chip
Tool geometry	[3,31,32,35,66,71,110–125]	[32,35,63,124,126–128]	[31,35,66,110,112,119,124,126,129,130]	[2,131,132]	[32,54,56,66,68,115,116,119,129,132,133]	[2,3,35,54,63,71,72,110–113,117,119,121,123,125,128,129,131–137]	[61]
Fibre orientation	[3,30,33,37,50,59,64,66,116,117,120,122,125,138–147]	[86,140,145,148,149]	[4,33,64,66,104,129,145,150–152]	[30,33,43]	[37,54,56,66,116,129,142,146,151,153]	[3,33,37,45,50,54,104,117,125,129,139,140,143–146,148,150,151,154,155]	[146,150]
Process parameters	[3,8,10,33,35,37,50,57–59,64–67,71,111–115,117,118,121,122,138,139,141,145,156–165]	[35,58,63,65,86,127,128,145,148,156,160,161,164,166–169]	[4,8,33,35,58,64,66,67,112,130,145,151,158,160,166,167,169–171]	[33,58,65,131,132,165,171–173]	[8,37,57,66,68,115,132,133,151,161,172,173]	[3,8,10,33,35,37,45,50,53,57,58,63,65,67,71,72],[111–113],[117,121,128],[131–134],[136,139,145,148,151],[156–158],[160–167],[169–172],[174–176]	[61]
Up vs down milling	[59,147]	[177]	[178]	[147,173]	[56,173,179]	[45,134,162,178,179]	NA
Width of cut	[3,10,50,57,64,71,113,117,138,156,160–162,164,165]	[86,156,160,161,164,166]	[64,150,160,166,171]	[165,171]	[57,161]	[3,10,50,57,71,72,113,117,150,156,160–162,164–166,171,175]	[61,150]
Cooling	[8,10]	[169]	[8,38,151,169,171]	[165,171]	[8,151]	[8,10,151,165,169,171,180]	NA

Table 2
Main advantages and disadvantages of available CFRP edge trimming technologies.

Technology	Advantages (+)	Disadvantages (−)
Conventional mechanical edge trimming (Fig. 2a, d)	good machined edge quality, easy to plan, easy to program, easy to implement	tool condition significantly affects quality, tool change is needed regularly, advanced cutting tool geometries are needed for high quality, technology is dependent on the fibre direction
Tilted mechanical edge trimming (Fig. 2b, e)	excellent machined edge quality, the dominancy of cutting force components can be controlled by the tool tilting	tool condition significantly affects quality, tool change is needed regularly, technology is dependent on the fibre direction, difficult to program and implement
Abrasive cutting with straight grinding wheels (Fig. 2c)	good machined edge quality, easy to plan, easy to program, larger material removal rate, low thermal load on the CFRP	tool condition significantly affects quality, only for straight contours, technology is dependent on the fibre direction, curvatures cannot be machined
Curved circular cutting technology (Fig. 2f)	excellent machined edge quality, low thermal loads on the CFRP, low cutting force, straight and curved contours both can be machined	difficult to program, complex contour of grinding wheel necessary, tool condition significantly affects quality, technology is dependent on the fibre direction, small convex curvatures cannot be machined
Ultrasonic vibration assisted edge trimming (Fig. 2g)	good machined edge quality, easy to plan, easy to program, contact time of the tool and workpiece is short,	tool condition significantly affects quality, tool change is needed regularly, faster tool wear speed, technology is dependent on the fibre direction
Laser beam cutting or abrasive water jet cutting (Fig. 2h)	excellent machined edge quality, minimal cutting force, no wearing tools, easy to plan, easy to program, technology is almost independent of the fibre direction	considerable heat affected zone, taper angle at AWJ cut edges, often bad surface quality, difficult to implement in the machining of large CFRPs
Laser scored edge trimming (Fig. 2i)	excellent machined edge quality, minimal cutting force at the edge, easy to plan, easy to program,	technology is almost independent of the fibre direction, expensive

influences of each factor in Table 1 are discussed in the following **Subsections 4.1-4.5**.

4.1. Tool geometry

The tool geometry primarily affects the machinability of CFRPs, as it directly affects the chip removal mechanisms, machining-induced delamination and burr formation mechanisms, chip evacuation, and heat dissipation effectiveness [128,160,181,182]. The cutting edge radius (CER), rake angle (γ), and clearance angle (α) are decisive geometrical parameters in the edge trimming of CFRP, as well as the helix angle (λ). Generally, the sharper the cutting tool (*i.e.* small CER, large positive rake, and clearance angles), the better the chip removal and surface generation; however, the sharper the cutting tool, the weakened the tool geometry resulting in more difficulty keeping the tool condition (without accelerated tool wear). Furthermore, the helix angle primarily affects whether the axial or radial force components dominate the process [125]. It is well known that the axial force component is responsible for machining-induced delamination generation in CFRPs [183]; thus, its avoidance or at least the minimization is highly recommended by the proper set of the helix angle. The λ can be set by the proper selection of the cutting tool and/or by the proper tilting of the cutting tool relative to the edge of CFRP [33].

Sheikh-Ahmad et al. [128] conducted edge trimming experiments in CFRPs using different cutting tool geometries and analysed the thermal aspects of the edge trimming process. They found that the tool geometry significantly influences the heat removal efficiency. They showed that the larger the chip size, the more the heat energy evacuated, which is beneficial from the point of view of matrix smearing avoidance. Hintze et al. [43] analysed the occurrence and propagation of machining-induced delamination through slot milling experiments in CFRPs. They proved that the tool sharpness is a key issue in CFRP milling, as the machining-induced delamination was found to be correlated to the tool condition. He et al. [143] confirmed the significance of tool sharpness in CFRP milling. They highlighted that the larger the cutting edge radius, the larger the probability of extended damage-affected zone formation. Gara and Tsoumarev [134,174] analysed the surface characteristics of edge trimmed CFRPs and reported that the transverse surface roughness of machined CFRP surfaces depends mainly on the tool geometry.

Ramulu [52] analysed the machinability of CFRPs through orthogonal machining experiments to provide support for tool geometry selection for edge trimming of CFRPs. He found that the rake angle has a significant influence on the cutting force and surface quality, but the influence of the clearance angle is slight. He proposed an optimal tool geometry for high-quality machining of CFRPs: rake angle of 6–7° and clearance angle of 17°. Voss et al. [66] conducted slot milling experiments and showed that the larger the clearance angle ($\alpha = 14^\circ$ and $\alpha = 21^\circ$ are tested), the smaller the contact area between the tool and composite. Consequently, a larger clearance angle is recommended to reduce the cutting force and tool wear and improve surface quality. Furthermore, Seeholzer et al. [184] stated that the initial clearance angle significantly affects the bouncing back height in the machining of CFRPs. Nevertheless, Liu et al. [119] found no obvious difference in the interlaminar damage between different α *and* γ *angles.*

Urresti et al. [129] investigated the influences of tool geometry parameters on tool wear and surface integrity of edge trimmed CFRPs. They found that a combination of a small helix angle and rake angle is beneficial from the point of view of tool wear; therefore, its combination is preferred to increase tool life. Hagino and Inoue [125] confirmed the advantage of a small helix angle, as they observed a significantly larger axial cutting force component at higher helix angles. Furthermore, as a result of the larger axial force, the probability of milling-induced delamination increased also by the larger helix angle. A helix angle of $\lambda = 0^\circ$ is recommended for mechanical edge trimming of CFRPs, as the axial cutting force component is minimal; thus, the machining-induced delamination and burrs are also expected to be minimal [69]. Considering that the helix angle plays an important role in edge trimming-induced geometrical defect generation, researchers and engineers proposed several advanced geometries of end mills (having compression effect), which special tools are discussed in **Section 5**.

4.2. *Fibre orientation*

The fibre orientation relative to the cutting motion (*i.e.* fibre cutting angle – θ) and the fibre content play one of the most important roles in chip formation mechanisms [185,186], cutting tool wear mechanisms [4,71], surface integrity [72,121,129,187,188] machining-induced delamination and burr formation [56,58] in carbon fibre reinforced polymer composites. Investigating and modelling of cutting mechanisms of edge trimming is extremely difficult due to the advanced tool geometries and complex movements; therefore, the cutting mechanisms of edge trimming are often derived from the orthogonal cutting experiences using the superposition principle. Four different chip removal mechanisms are associated with CFRP machining, depending on the fibre cutting angle. Ramulu [52] observed that chip removal in CFRPs is dominated by (i) mode I and II loading, resulting in delamination at a fibre cutting angle of 0°, (ii) compression-induced shear across the fibre axis combined with interracial shearing at a fibre cutting angle of 45°, (iii) compression-induced fracture perpendicular to the fibres and interlaminar shear fracture along the fibre/matrix interface at a fibre cutting angle of 90°, (iv) combined macro fracture at a fibre cutting angle of 135°. Considering that the edge trimming tool rotates, it gets to contact with the fibres in a wide range, depending mainly on the feed direction relative to the fibres (*i.e.* fibre orientation) and the width of cut (a_e) [4]. Therefore, the technology planning of edge trimming of CFRPs is even more challenging.

Wang et al. [117] analysed the distribution of the fibre-matrix interface cracks in the edge trimming of CFRPs. They showed that the fibre orientation has a significant influence on the fibre-matrix interface cracks. Kim et al. [64] conducted edge trimming experiments in CFRPs and concluded that fibre orientation plays a significant role in flank wear. Xu et al. [50] investigated the effect of tool vibration on chip formation and cutting forces when edge trimming CFRPs. They found that the fibre orientation significantly affects the chip formation and cutting forces consequently. Considering that fibre reinforcements determine the machinability of CFRP composites [155], the fibre content also plays a significant role in evaluating edge trimming CFRPs; however, the number of studies is limited in this area. Song et al. [155] found that the fibre distribution affected the surface roughness of edge trimmed CFRPs. They observed a 9.08–14.28 times higher contribution of carbon fibres to the surface roughness than the matrix material. Ghafarizadeh et al. [146] analysed the edge trimming of CFRPs through finite element analysis. They concluded that the friction coefficient between the tool and the composite material is highly influenced by the carbon fibre orientation. Furthermore, the distinct chip forms are also dependent on the fibre orientation, according to the study of Koplev et al. [189]. Hamedanianpour and Chatelain [132] recognised the worst surface integrity of edge trimmed CFRPs at a fibre cutting angle of 135°. A significant amount of matrix cracking and fibre pull-out was observed in this unfavourable condition.

Li et al. [37] observed that machining-induced burrs are highly correlated to the fibre cutting angle, similarly to the experiences gained through the drilling of CFRPs [190]. Hintze et al. [43] specified that the fibre orientation on the top and bottom of the CFRP plate is decisive in machining-induced geometrical defect generation, while the inner layers have a slight role because those are mechanically supporting each other's against buckling [37]. They also determined optimal conditions for edge trimming CFRPs: delamination and burr-free edges can be machined at a fibre cutting angle of $0^\circ < \theta < 90^\circ$, even by using a slightly worn cutting tool. Furthermore, the fibre cutting angle of $90^\circ \leqslant \theta < 180^\circ$ is unfavourable because this condition results in significant burrs and delamination.

The fibre cutting angle has a significant influence on the cutting force in the edge trimming of CFRPs [120]. Maximum cutting forces were recorded by He et al. [142] at fibre cutting angle range of $55^\circ < \theta < 70^\circ$, and minimum forces were recorded at fibre cutting angle range of $5^\circ < \theta < 15^\circ$. Karpat et al. [116] developed a mechanistic force model for the milling of unidirectional CFRPs. They found the fibre cutting angle of 45°favourable from the point of view of cutting force and surface quality. The maximum of the radial and tangential cutting force component was found at fibre cutting angles of 140° and 120°, respectively.

4.3. *Process parameters*

The feed and the cutting speed are those process parameters of edge trimming that can be easily varied on the machine tool and optimised. Considering that the feed has a direct effect on the chip cross-section, thus on the cutting force [120], it has a significant effect on the delamination formation, tool life, and cutting temperature [171]. Generally, the larger the feed, the larger the cutting force and the higher the probability of machining-induced geometric defect formation [147, 157,191,192]; therefore, the minimization of the feed is recommended. On the other hand, the larger feed is beneficial from the point of view of material removal rate (MRR) and cutting temperature. Considering the contradictory feed selection recommendations, the proper set of feed has to be selected based on the target application. The influence of cutting speed is not as direct as the feed's; however, it has a significant influence on the cutting temperature, tool wear, and matrix smearing [10].

E-Hofy et al. [127] conducted edge trimming experiments in CFRPs and found that an increase in the feed from 0.03 mm to 0.06 mm reduced the cutting temperature by 18 %. Bi et al. [130] observed that a too-small feed (*e.g.* 0.01 mm) is unfavourable because it induced more accelerated tool wear. Sheikh-Ahmad et al. [128] highlighted that the larger the feed, the larger the chip thickness; therefore, the larger the heat evacuated from the cutting zone. The increase of feed is therefore recommended until the resultant force reaches the critical force from the point of view of delamination formation. The influence of the feed on the tool wear in the edge trimming of CFRPs was analysed by Palanikumar et al. [193]. They found that the larger feed, the smaller the speed of tool wear. Furthermore, the tool temperature is also decreased by an increase in the feed. Madjid Haddad et al. [63] also reported the benefits of large feeds. They observed less harmful particles in the air at larger feeds. Slamani et al. [159] studied the combined effects of machining parameters on cutting force components during high-speed robotic trimming of CFRPs. They found that the feed has a more significant influence on the cutting force than the cutting speed or robot configuration.

It is reported by numerous works that the feed has a direct influence on the nominal surface characteristics of CFRPs [194]; its optimisation is therefore essential. Davim and Reis [195], Palanikumar et al. [193] and Madjid Haddad et al. [63] conducted machining experiments in CFRPs, and each concluded that the larger the feed, the worst the surface quality is, *i.e.* the average surface roughness is larger, and the surface defects are more severe. In contrast, Voss et al. [66] and Madjid Haddad et al. [63] observed that larger feeds are more beneficial from the point of view of average surface roughness. Voss et al. [66] proposed a feed of 100 μm/rot against the 30 μm/rot. Gara and Tsoumarev [174] conducted CFRP slotting experiments with knurled end mills and found that feed is the key factor influencing surface roughness. In addition to the reported benefits of lower feeds on the surface quality, Thakur et al. [172], Khairusshima et al. [175] and Sheikh-Ahmad et al. [131] proved the benefits of lower feeds in machining-induced delamination minimization.

Gara et al. [118] and Palanikumar et al. [193] investigated the effect of process parameters on the cutting temperature in the edge trimming of CFRPs. They found that the larger the cutting speed, the more heat generated and the larger the cutting temperature. For example, increasing the cutting speed from 200 m/min to 350 m/min results in an average cutting temperature rise of 25 %, according to EL-Hofy et al. [127]. Therefore, the matrix is softening and results in smaller cutting forces, as it is confirmed by Duboust et al. [120]. However, the larger cutting speeds may result in accelerated tool wear, according to Palanikumar et al. [193]. Haddad et al. [88] found that the larger the cutting speed, the more thermal damage on the edge trimmed surfaces of CFRPs. Madjid Haddad et al. [63] reported that fewer harmful particles were found in the air at lower cutting speeds.

Although the effect of cutting speed on surface quality is often difficult to determine in the edge trimming of CFRPs [111], Sundi et al. [136] found that cutting speed has the most decisive influence on surface quality among process parameters. Davim and Reis [195] and Palanikumar et al. [193] reported that the larger the cutting speed, the lower the average surface roughness. This may suggest that the surface quality is better in the case of higher cutting speeds; however, the conventional roughness parameters may be misleading, as a smoother surface may result from a significant matrix smearing that can hide potential surface defects [140]. Thakur et al. [172] propose a higher cutting speed for minimal surface roughness and a lower cutting speed for minimal edge trimming-induced delamination. Sheikh-Ahmad et al. [131] reported a decreased delamination depth and surface roughness at larger cutting speeds.

4.4. Up vs down milling and width of cut

Considering that the range of fibre cutting angle – that primarily affects chip removal of CFRPs – depends on the radial depth of cut (*i.e.* the width of cut – a_e) and milling strategy (*i.e.* up and down milling), their proper selection and optimisation are recommended [59,66,195–197]. It has to be mentioned that the depth of cut (a_p) is also a decisive factor in the milling of CFRPs; however, the influence of a_p is usually not investigated through edge trimming, as it is often set to equal the thickness of the CFRP plate. Generally, the proper set of the a_e, and the down milling strategy is recommended to machine good-quality geometric features in CFRPs [66].

Voss et al. [66] conducted slot milling experiments in CFRPs and observed fewer burrs on the down-milled side of the slot than on the up-milled side. Wang et al. [56] confirmed that the down milling of CFRPs is more beneficial from the point of view of burr formation. On the other hand, Su et al. [153] reported that the burr is more severe on the down-milled side when the fibre orientation angle (*i.e.* feed direction relative to the fibre direction) is 90°. Hintze and Brügmann [173] investigated the machinability of CFRPs through slot milling experiments and measured the machining-induced burrs on the machined edges of the slots. They observed that the burr lengths on up- and down-milling edges only depend on feed direction. Furthermore, when milling circular contours, the burr length is larger on the outer edge, and all burrs decrease with smaller circle radii. Gara and Tsoumarev [134] found that the surface roughness of up-milled surfaces is smaller than that of down-milled. In contrast, Rimpault et al. [178] reported no significant difference in average surface roughness of up- and down-milled edges. Geier [198] analysed the influence of fibre orientation on the cutting force. He found that the radial force component is more sensitive to the fibre orientation at up milling than at down milling.

Liu et al. [57] investigated the fracture mechanism evolution through the edge trimming of CFRPs. They found that the larger the width of cut, the more intensive the damage propagation of bending fracture is. Considering that bending fracture often results in uncut materials, its avoidance is critical. They recommend using small width of cut (a_e of 0.1–1.0 mm was investigated). Wang et al. [179] analysed the edge trimming-induced burr length in CFRPs. They observed that the larger the width of cut, the larger the burr length is. Considering that the fibre cutting angle range of $90° < \theta < 135°$ should be avoided in the milling of CFRPs due to inappropriate chip removal mechanisms (it is dominated by microfracture and bending) arising, they recommend reducing the width of cut until this unfavourable fibre cutting angle range is avoided. Zenia et al. [199] investigated the chip formation mechanisms and damage depth evolution in the edge trimming of CFRP composites. They observed that both chip formation mechanisms and damage depth are significantly influenced by the width of cut rather than the rake angle of the cutting tool. Masek et al. [161] observed that the larger the radial depth of cut, the larger the active force component, and the larger the delamination length and the cutting temperature also. Considering that a larger a_e results in a longer contact between the composite and the tool, the process is expected to be therefore more critical from the point of view of tool condition and delamination.

Kerrigan and O'Donnell [156] conducted edge trimming experiments in CFRPs and analysed the relationship between cutting temperature and polymer degradation. They found that the radial depth of cut has a significant influence on the cutting temperature. The radial depth of cut accounted for approximately 20 % of the energy input in the edge trimming process. Sheikh-Ahmad and Mohammed [164] reported that a too-large width of cut ($a_e = 12.7$ mm = diameter of the tool) results in a temperature that is higher than the glass transition temperature of the epoxy matrix. Therefore, the proper selection of a_e is essential to manufacture high-quality edges in CFRPs. Li et al. [166] found that the radial depth of cut has a significant influence on the tool wear, as the feed has. From the point of view of harmful particle minimization in the air, a larger radial depth of cut (from 2 mm to 3 mm) is recommended by Nguyen-Dinh et al. [61]. Hintze et al. [177] compared the temperatures of the machined workpiece surface (measured using a pyrometer at a short distance behind the tool) between up and down milling strategies for two different width of cut values. While the temperatures during up milling and down milling were similar at low width of cut ($a_e = 1$ mm), it was found to be significantly (approx. 100 °C) higher at the down milled surface in case of high width of cut ($a_e = 12.7$ mm).

Although experiences show that the cutting strategy influences chip morphology during edge trimming of CFRPs, there is no relevant published information on the influential properties of up vs down milling on the chip morphology.

4.5. Cooling

The cooling of edge trimming of CFRPs induces better tool matrix interaction by reducing friction at their interface, helps chip evacuation, and may make the fibres more brittle to be cut more effectively. However, it makes the dust-like carbon chips more difficult to filter and remove and may be absorbed by the polymeric matrix. Researchers investigated the influences of different cooling strategies (*i.e.* flood, internal, minimum quantity lubrication (MQL), air, cryogenic) on the cutting energetics and machining-induced burrs. Wang et al. [200] pointed out that the polymeric matrix becomes softer, resulting in accelerated burr formation and reduced strength if the cutting temperature exceeds the glass transition temperature (T_g). Therefore, an effective cooling liquid would be beneficial to be used to support the edge trimming of CFRPs. Cryogenic edge trimming uses liquid nitrogen to reduce cutting temperature. In addition to that, the T_g can be avoided by cryogenic cooling; the fibre reinforcements become more brittle, resulting in better chip removal characteristics, as was proven by Seo et al. [201]. Cunningham et al. [2] conducted dry and cryogenic edge trimming experiments in CFRPs using different cutting tools. They observed a significantly improved surface quality when cryogenic cooling was applied compared to the dry machining (28.1 % improvement), independently of cutting tool geometry. They also reported that cryogenic cooling increases the tool life. Kumar and Gururaja [180] also concluded that the edge trimmed surface quality is significantly better in the case of the application of cryogenic cooling compared to the dry condition. Furthermore, they observed larger cutting forces at the cryogenic edge trimming processes.

Helmy et al. [10] investigated the influence of flood coolant in the edge trimming of CFRPs. They found that the application of flood coolant significantly decreases the bouncing back effect. Furthermore, the cutting force was smaller when the flood coolant was applied compared to the mist coolant. Khairusshima et al. [38,169,171] investigated the influence of the application of chilled air cooling on the cutting temperature, delamination and tool wear. They could achieve smaller cutting temperatures by the application of chilled air, which prevented the cutting tool from being damaged. Furthermore, the probability of machining-induced delamination formation was smaller, and the tool wear was less accelerated when the chilled air was applied compared to the dry condition. Therefore, chilled air applications may have the potential to improve edge trimming ability of CFRPs. Cococcetta et al. [151] investigated the surface finish, burr formation, and tool wear during the machining of 3D-printed CFRPs using MQL and dry conditions. Their results show that the quality of the edge trimmed surface and tool wear improved under MQL compared to dry conditions. Furthermore, the burr formation was also significantly reduced by using MQL.

According to the best knowledge of the authors, there is no available published information on the influential properties of cooling on the chip morphology.

5. Cutting tools for edge trimming of CFRPs

Machining processes such as edge trimming, milling, and drilling are frequently used to finish composite parts into desired shapes. Due to the fact that CFRP is inhomogeneous in nature, it may cause unwanted consequences such as rapid tool wear, fibre pull-outs, surface burning, delamination, smearing, *etc.* Specifically, when utilizing a helical tool for the edge trimming process, delamination is strongly dependent on the tensile axial cutting force component. Colligan et al. [202] studied the delamination damage of graphite/epoxy surface plies caused by the edge trimming process using PCD and helical helix carbide end mill tools. It was observed that surface ply delamination appears to occur in three distinct types, depending on the orientation of the surface fibre relative to the path of the cutting edge. Therefore, it is significant to choose the most appropriate cutting tool considering the tool's geometries and materials. Currently, there are various types of materials available for cutting tools dedicated to the edge-trimming of composite materials. According to Sundi et al. [182], three main characteristics, including hardness, toughness, and overall strength, are taken into consideration when selecting the material. It is anticipated that the cutting tool will have relatively higher hardness and toughness properties than the machined CFRP. In such a manner, the material with higher toughness properties could resist more chipping and fracturing effects during the machining process. In contrast, hardness refers to the ability of the material to localized plastic deformation, which changes inversely to the toughness. Future research is expected to focus on increasing the toughness behaviour of tools with a constant hardness property.

In accordance with Fig. 3, polycrystalline diamond (PCD) and solid carbide body end mills are the two types of cutting tools that are frequently employed for edge trimming CFRPs. First of all, the PCD tool is made of two major components, namely the PCD blanks and the body/holder. It is widely used due to its superior resistance to wear rate. Additionally, a number of experiments have demonstrated that the PCD cutting tool has good surface roughness but the lowest resistance to bending [182]. It also has extensive hardness properties with higher thermal conductivity compared with other single-crystal diamonds; thus, it could sustain an abrasive resistance. El-Hofy et al. [203] conducted a comparative study on diamond-liked-carbon (DLC) coated carbide end mills and PCD tools. The authors concluded that all of the DLC-coated carbide end mills examined wore rapidly; however, most of the PCD tools reached a cut length of 28 000 mm without surpassing 0.3 mm flank wear. The authors revealed that the PCD tools produced a sufficient surface quality without reducing tool wear rate during the slotting of CFRP materials. Later, staggered PCD cutter geometry was designed by Chen et al. [204] and Liu et al. [205] as it has substantial resistance to the wear rate and superior burr suppression compared with the conventional PCD tool having a helix angle of 0°. The cutting edge of the staggered PCD cutter had an inclination angle of 5°, while the inclination angle of its adjacent cutting edge was in the opposite direction. Overall, the tool body chosen material is K40UF cemented carbide. However, according to López de Lacalle et al. [206], one of the limitations of PCD tools is that they are not economically practical due to their high cost.

Another cutting tool is the solid carbide end mill which can be further divided into two types, namely the helical helix tool and router/burr/interlocking geometry. The helical helix tool is most broadly used for metallic materials, and it has either a right-hand or left-hand helical helix shape depending on the application. Devi et al. [208] obtained a predictive cutting force model for helical end milling using mechanistic modelling techniques and neural network approximation. Davim et al. [195] investigate the effect of surface damage with two different helical helix end mills. It was discovered that two-flute end mills with specific geometries generated better surface quality than six-flute helical helix end mills. The authors also found that for both end mills, the feed rate is the cutting parameter with the most significant statistical and physical

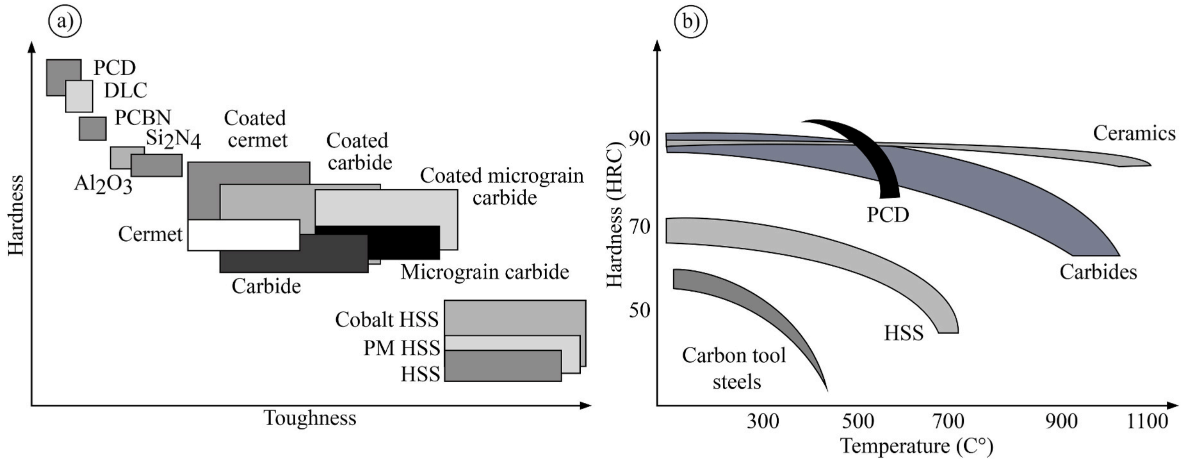


Fig. 3. (a) Overall hardness and toughness level for cutting tool materials; (b) Hardness of major tool material in HRC versus temperature, redrawn based on Ref. [207].

effect on surface roughness (94.1 % and 77.5 %) and delamination factor (83.9 % and 85.9 %), respectively. Moreover, according to Uhlmann et al. [209], high-speed cutting (HSC) of CFRPs using eight-flute end mills tungsten carbide material enables productivity growth and, as a result, offers significant cost-saving potential.

By reducing waste and the need for post-machining work, HSC milling of CFRPs can also enhance workpiece quality. Can et al. [76] reported that an increase in the number of teeth or flutes decreases the deformation on the trimmed edges. Recently, a new cutting tool was designed by Wang et al. [210] known as the left-right end mill tool, which effectively removes the burrs, delamination, and tearing defects, as depicted in Figs. 4 and 5. While end mills with advanced tool paths such as conventional helical milling, tilted helical milling and wobble milling can be used for better machining. The researchers analysed the kinematic of conventional helical milling and tilted helical milling, and it showed that effective cutting speed could be zero in the case of conventional helical milling as well as in the case of tilted helical milling with proper technological parameters, a scenario where effective cutting speed is zero can be avoided [11]. Therefore, advanced machining technologies, as mentioned above, can be applied in order to effectively minimise geometrical defects and tool wear.

The second kind of solid or (uncoated/coated) carbide end mill geometry is called burr or router tool, as shown in Fig. 6. This type of tool has been widely employed by industries since it is less expensive than a PCD tool and is extremely efficient in precisely shearing/trimming FRP materials. Janardhan et al. [211] examined characteristics of the solid carbide router burr tools as it has been popular for trimming fibreglass due to high wear resistance and ability to produce a clean cut at relatively high feed rates. Alternately, it also caused the tool to be brittle and highly susceptible to fracture. Based on the experiments done by Haddad et al. [212], the defects induced by the burr tool are mainly located at the plies oriented at 45°. These defects will be assimilated into craters or even cracks. The presence of these cracks induces areas of stress concentration which will develop relatively small values of compressive strength and inter-laminar shear strength. Also, the fatigue tests exhibit that the higher endurance limit corresponds to those specimens trimmed by the burr tool for any machined surface quality.

König et al. [214] studied the performance of composite machining, and they suggested employing ‘diamond cut’/burr tool geometry for glass and carbon fibres while utilizing an opposed helical design for aramid fibres for optimal outcomes. Janardhan et al. [211] investigated the up-and-down (UD) milling of CFRP utilizing a diamond interlocking/burr tool, and it was identified that up-milling with burr tools would produce less delamination and surface roughness in terms of machining damage. Overall, the best surface was produced when the fibres were parallel to the tool feed direction. Duboust et al. [215] claimed that despite being evaluated at a high feed rate, multiple teeth/burr geometry (diamond coated) tools provided an acceptable surface quality in contrast to a polycrystalline diamond (PCD) tool. The authors observed that the multi-tooth milling tool or burr tool was the most effective for trimming various types of composite materials. Also, an observation has been made by Bilek et al. [216] stated that the

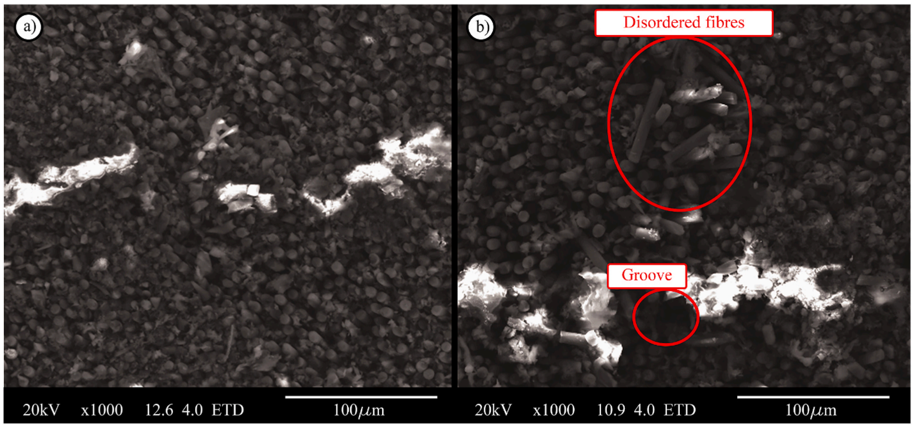


Fig. 4. Comparison of machined composite surfaces by different tools: (a) the right-edge milling tool; (b) the left-right edge milling tool, redrawn based on Ref. [210].

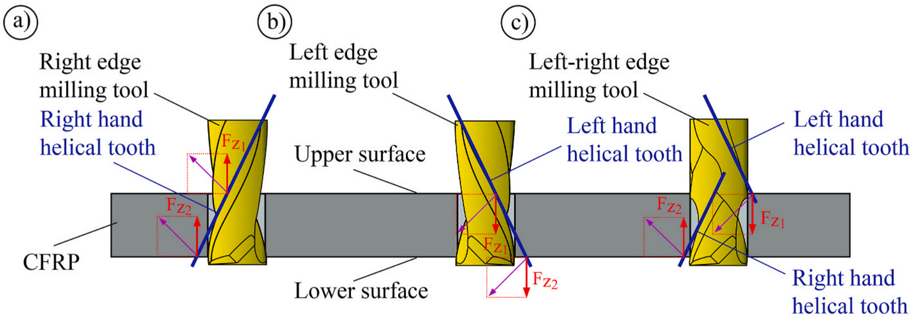


Fig. 5. Effect of milling tool structure on the trimming of CFRPs: (a) the right edge (up cut) milling tool and (b) left edge (down cut) milling tool; (c) the left-right edge (dual helix or compression) milling tool, redrawn based on Ref. [210].

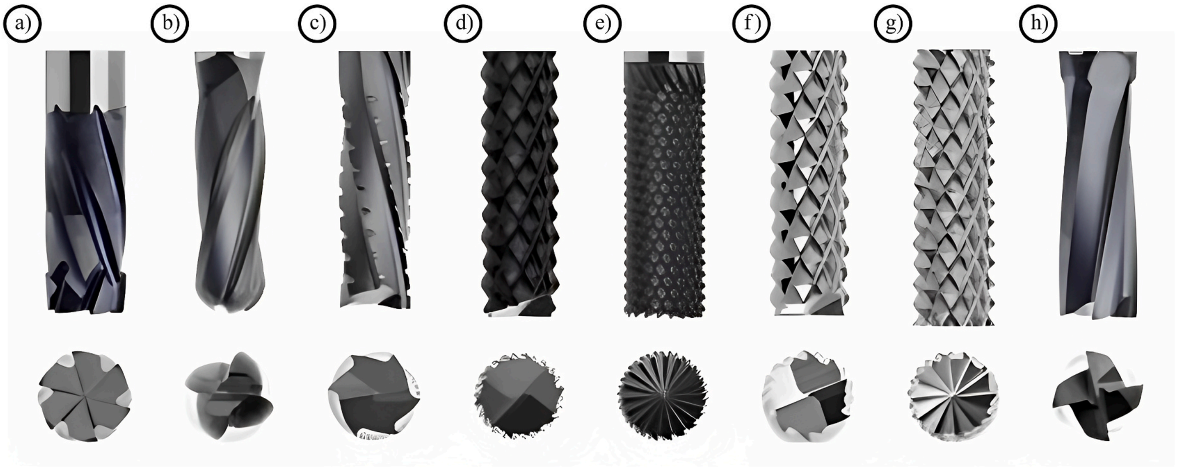


Fig. 6. Representative advanced tool designs for the edge trimming of CFRP composites: (a) coated multi-flute dual helix end mill (also known as compression end mill), (b) coated multi-flute ball nose end mill, (c) coated multi-flute down cut helical end mill with chip breakers, (d) coated coarse honeycomb mill, (e) coated fine honeycomb router, (f) uncoated coarse honeycomb mill, (g) uncoated coarse honeycomb router, (h) coated multi-flute down cut helical end mill; redrawn based on Ref. [213].

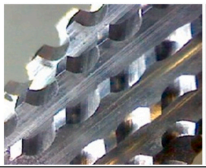
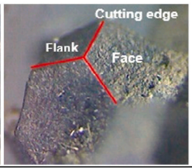
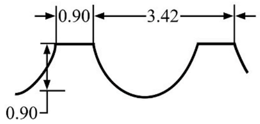
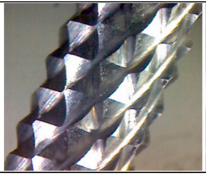
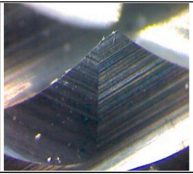
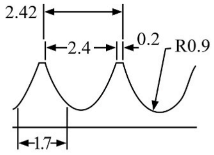
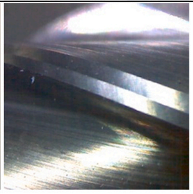
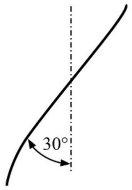
Tool	Specification	Image of the tool	Tooth shape	Tooth profile
Tool T1	Pitch = 3.42 mm No. of flutes = 12 Tooth Shape: Trapezoidal			
Tool T2	Pitch = 2.42 mm No. of flutes = 12 Tooth Shape: Pyramidal			
Tool T3	Helix angle 30° No. of flutes = 4 Tooth Shape: Helical fluted			

Fig. 7. Morphologies of the examined cutting tools for the edge trimming of CFRPs (T1, T2 & T3), redrawn based on Ref. [217].

router/burr type tool is more appropriate compared with the PCD tools for edge trimming at a certain point as the PCD tool exhibited a lower cutting efficiency. This is further proved by Prakash et al. [217], who studied the influence of trimmed surface quality in high-speed milling of CFRP composites by modifying three kinds of tool configurations, as illustrated in Fig. 7.

These three kinds of tools include two distinct detailed burr-type tools (T1 and T2) and helical helix geometry (T3), as detailed in Fig. 7. When cutting CFRP materials, it was discovered that the tool T1 produced lower cutting forces, a moderate level of surface roughness and no delamination. Since the cutting tooth has a trapezoidal shape and an even larger cutting area, it is the most effective among the three tools and causes minimal surface damage to the edges that are being trimmed. As compared with the other two types of tools, the tool T2 produced a greater cutting force and rougher surface. More indentations are made on the surface of the workpiece by the cutting tooth's tiny flat-edged pyramidal shape. As a result, the surface roughness will increase. Lastly, the helical helix end mill was found to produce greater cutting pressures and more delamination due to the continuous flutes with a higher helical angle. Gara and Tsoumarev [134] conducted a series of comparative studies on several micro-grain burr tools for slotting CFRP materials that were divided into fine, medium and coarse varieties. The authors found that the transverse surface roughness was not significantly affected by the cutting settings. However, it was revealed that the slotted surface quality in the transverse direction was mostly determined by the tool geometry. In comparison with the other two types of geometries, the fine grain geometry of the burr tool was said to be the sort of geometry that was most highly recommended for usage in slotting CFRP material (smooth and coarse).

Currently, extensive studies have been conducted to determine how the cutting parameters impact the cutting tools during the trimming of CFRPs. For instance, Sheikh-Ahmad et al. [218] and Haddad et al. [212] addressed the effects of cutting temperatures generated by various tool geometrical designs. They stated that the heat produced during the cutting/shearing operation was mostly evacuated by the chips. As a result, the proportion of heat energy transferred away during machining was dictated by the size of the chips created, also known as chip thickness. The authors also pointed out that utilizing a multi-tooth tool will minimise defects compared with conventional helical cutting tools in dry conditions. Sundi et al. [182] have also demonstrated the influence of machining parameters, namely cutting speed (v_c) and feed rate (v_f), on the surface quality in edge trimming of a specific CFRP material. Karpat et al. [219] generated a force model for the up-and-down (UD) cutting tool; however, very limited literature can be found to address the practical effects of using this cutting tool geometry. Cunningham et al. [2] proved that cryogenic CNC machining improves the delamination length with the UD cutting tool for edge trimming CFRP, whereas the multi-toothed cutting tool was highly susceptible to chipping under cryogenic CNC machining. According to Hocheng et al. [220], diamond cutter (Ads) and abrasive water-jet machining are recommended for use to reduce the damage induced by the trimming process.

Finally, Table 3 also summarizes the fundamental effects of various types of cutting tools dedicated to the edge trimming of CFRPs from the open literature. It is shown that the use of functionally-designed cutting tools or advanced tool materials is more appropriate for the high-quality trimming of CFRPs. Additionally, through the rigorous literature survey in this section, the edge trimming of CFRP composites requires more specific attention to the comprehensive optimisation of various machining input parameters such as tool geometries, tool materials, cutting parameters (cutting speed and cutting depth), *etc*., in order to eliminate surface defects induced by machining that could have a severe impact on the strength of the composite material. In conclusion, a series of research works have achieved an agreement that the router/burr type tool is more recommendable for edge/side trimming of CFRP materials. However, many scholars worldwide are still focusing on determining the perfect tool geometrical design for milling/trimming CFRP materials without considering the simultaneous use of advanced machining technologies. In the future, more attention should be paid to the combined development of superior tool geometries/materials and advanced cutting methods such as ultrasonic vibration assisted cutting, helical cutting or wobble machining, curved circular cutting, and laser scored machining, for the high-quality trimming of CFRPs.

Table 3
Summary of cutting tools used for edge trimming CFRPs.

Reference	Cutting tool	Key conclusions
Sundi et al. [182]	PCD tools	They produce a relatively good surface roughness and the poorest bending mechanisms resistance.
El.Hofy et al. [203]	Diamond-liked-carbon (DLC) coated carbide end mills	All the DLC-coated carbide end mills wear rapidly compared with the PCD ones.
Chen et al. [204]	Staggered PCD cutters	They have substantial resistance to the wear rate and superior burr suppression.
Sundi et al. [182]	Helical helix tools	They are most broadly used for metallic materials, and it has either a right-hand or left-hand helical helix shape depending on the application.
Davim and Reis [195]	Two-flute end mills	They generate better surface quality than the six-flute helical helix end mills.
Davim and Reis [195]	Six-flute helical helix end mills	They are highly wear-resistant and able to produce a clean cut, but they cause the tool to be brittle and highly susceptible to fracture.
Uhlmann et al. [209]	Eight-flute end mills	They enable productivity growth and offer significant cost-saving potential.
Wang et al. [210]	Left-right end mill tools	They effectively remove the burrs, delamination, and tearing.
Gara and Tsoumarev [134]	Micro-grain burr tools	They are highly recommended for usage in slotting CFRP materials.
Sundi et al. [182]	Router/burr/ interlocking geometries	They have been popular for trimming fibreglass due to their high wear resistance and ability to produce a clean cut at relatively high feed rates.
Duboust et al. [215]	Multiple teeth/burr geometry (diamond coated) tools	They provide an acceptable surface quality.

6. Future trends and outlook

Considering that the CFRP applications are continuously increasing mainly due to the excellent specific mechanical properties of CFRPs and the enlarged experience and expertise in their manufacturing, remarkable attention will govern the future research and development of CFRP edge trimming processes and technologies. Although high-quality edges in CFRPs are manufacturable by current optimised edge trimming technologies, these require further development in order to increase the wear resistance of cutting tools, the capacity of prediction and inspection of edge trimming-induced geometrical defects and machined features, intelligent support of parameter selection and process sustainability.

Even the early research results of composite machining highlighted that the fibre cutting angle (θ) plays an important role in determining chip removal mechanisms [52], thus quality of machined geometrical features and process efficiency. Although the fibre cutting angle can be calculated through the information of the angular position of the cutting tool (by monitoring the spindle) and the nominal fibre orientation in the case of long continuous fibre reinforced unidirectional and bidirectional composites [66], it is unknown or difficult to predict in the case of non-continuous reinforcement structures. For example, the fibre orientation in polymer composites reinforced by chopped carbon fibres (*i.e.*

forged CFRPs) cannot be planned, as the chopped fibres are positioned stochastically in the matrix [51]. Therefore, the identification (*i.e.* determination of positions, sizes and orientations) of chopped fibres is essential to calculate the fibre cutting angle and make the machining-induced geometrical defect predictable and controllable [51]. Future work is needed to increase the efficiency of current fibre detection methods by using advanced digital image processing and/or machine learning techniques (*e.g.* patch distribution modelling for anomaly detection and localization). On the other hand, the accelerated developments of 3D printing of CFRP technologies will possibly make an opportunity to manipulate the fibre direction around the nominal edges of geometrical features to ensure the proper cut of fibres without modifying the resultant strength of the CFRP parts considerably [179,221,222]. However, no studies aim to study this technology in the open literature.

Although current advanced tool geometries are capable of machining excellent qualities of geometric features in CFRPs, considerable attention will be decisive in the future on the tooling of CFRP machining, as the machinable length (*i.e.* tool life) is difficult to predict and moderate. Towards to increase the tool life, Ashworth et al. [110] proposed increasing the self-sharpening behaviour of cutting edges when machining CFRPs. Considering that the underlying mechanisms of cyclical sharpening of cutting edges are still unknown, it is difficult to be controlled. On the other hand, a significant effort has to be made the improvements current algorithms aiming to support the tool change using machine learning [223]. The better performance of these prediction algorithms is required to determine the remaining tool life more precisely in order to increase tool utilisation and process sustainability.

Current CFRP edge trimming operations are conducted in dry conditions mainly due to the problematic nature of carbon chips, the difficult implementation of cooling in the robotic trimming of large CFRP parts and polymer absorption behaviour [224]. Considering that the cutting temperature when edge trimming CFRP may vary between 180 and 350 °C [127], it often reaches the glass transition temperature (T_g), resulting in matrix softening and inappropriate surface generation mechanisms. Therefore, often small feeds are selected to decrease cutting temperature, cutting force and related geometrical defects. However, the smaller the feed, the smaller the material removal rate is. The application of appropriate cooling technology would make the selection of larger feeds possible. Researchers published numerous experiences in the benefits of applying cryogenic cooling technologies [2,8,201]; however, these applications fail to protect the environment making the machining process less sustainable. Therefore, the development of a controlled, minimum-quantity cryogenic cooling technology would be beneficial, and investigations may be decisive in the future.

The benefits of the manipulation of effective cutting geometries by tilting the cutting tool are proved by researchers in many CFRP applications [11,32,40,225]. Current tilted edge trimming operations are tilting the cutting tool along one axis, but no studies were found analysing the effectiveness of a complex tilting technology. For example, Pereszlai et al. [60] analysed wobble milling technology to produce high-quality holes in CFRPs, by tilting the cutting tool along two axes. In the future, a novel edge trimming technology could be developed inspired by wobble milling to decrease the probability of edge trimming-induced geometrical defects. However, these advanced technologies are often difficult to implement in an industrial environment because the edge trimming of large CFRP products by industrial robots faces considerable precision limitations [65,159,226]. Although Slamani et al. [154] made a great effort to eliminate trajectory deviation of robotic trimming CFRPs and could achieve similar qualities to CNC machining, the robotic trimming of CFRPs need to be further optimised in order to make it a relevant alternative to CNC machining.

Measurement and quantification of machining-induced geometrical damages and surface quality of edge trimmed CFRPs is still a key issue [55], as there are no existing internationally accepted standards or directives. This lack of support results in numerous factors (burr factor, burr length, contour burr factor, delamination factor, equivalent delamination factor, delamination area, two-dimensional delamination factor, corrected delamination factor, inverse delamination factor, adjusted delamination factor, minimum delamination factor, *etc.*), measurement methods (manual processing, digital image processing, image differencing, machine learning *etc.*) and difficulties in interpreting the published results. Therefore, standardization of machining-induced composite-specific geometrical defects is recommended to guide researchers and support the industry in interpreting the expertise published in the open literature. Although the average surface roughness (R_a) is the most commonly used parameter characterizing machined surfaces in metallic materials, researchers pointed out that it is not an appropriate indicator of surface quality in polymeric fibrous composites. Yet there are still many researchers who use R_a to quantify machined surface quality in CFRPs. Voss et al. [227] stated that low average surface roughness does not guarantee that there are no machining-induced defects in the surface, as they may be hidden by the smeared matrix, as was confirmed by the study of Slamani et al. [67] and Ashworth et al. [110].

7. Conclusions

In the present review study, recent challenges and applications of edge trimming of carbon fibre reinforced polymer (CFRP) composites are critically reviewed and discussed. According to the present study, the following conclusions can be drawn:

- The following key challenges determine recent investigations in edge trimming of CFRPs: (i) difficulty in avoiding machining-induced delamination and burr formation, (ii) a significant amount of dust-like chip generation, (iii) abrasive wear effect of carbon fibres on the cutting tool, (iv) often unknown rest material resulting in a difficult to consider fibre orientation, fibre content and width of cut. While the suppression of geometrical damages can be solved by a proper set of process parameters and tool geometry, its sustainability is still questionable, mainly due to the accelerated tool wear and its difficulty in predicting and measuring nature.
- Researchers proposed tilted edge trimming and curved circular cutting technologies for high-quality edge trimming of CFRPs. Although the benefits of these advanced technologies are considerable compared with the conventional edge trimming technologies, their widespread in the industry is not supported properly by the amount and diversity of recent published technical expertise. A novel edge trimming technology would be beneficial to be developed on the analogy of wobble milling holes in CFRPs.
- Tool geometries and materials are two essential factors affecting the trimming quality of CFRP materials and tool performances. Previous studies have indicated the benefits of using functionally-designed tools (such as conventional helical end mill – right/left-handed, conventional end mill with zero helix angle, compression end mill, honeycomb end mill, etc.) in producing better quality CFRPs. However, these tool geometries must work under the optimal cutting parameters to yield the best trimming results, which requires a comprehensive matching between the tool geometries/materials and process parameters. Additionally, specially-designed tools can work together with advanced machining technologies, such as ultrasonic vibration-assisted cutting, helical cutting, or wobble machining, for the high-quality trimming of CFRPs. More research endeavours are expected to make on this aspect. Additionally, stringent control of the tool wear and failures is also required to ensure the high cutting performances of tools dedicated to the trimming of CFRPs.
- In the future, significant attention will be on the (i) determination of the width of cut, fibre orientation and fibre content of the rest material in CFRPs, (ii) development of fibre detection methods, (iii) investigation of self-sharpening of cutting tools when cutting CFRPs, (iv) development of algorithms predict remaining cutting tool life,

(v) development of a controlled, minimum quantity cryogenic cooling technology, (vi) improvement of the accuracy of robotic trimming and (vii) improvement of the measurement and quantification of edge trimming-induced geometrical damages. Moreover, with the emergence of intelligent manufacturing, the edge trimming of CFRPs will develop toward the direction of flexibility, digitalization, and intelligence. In the future, researchers can try to apply intelligent manufacturing enabling technologies such as the Internet of Things, big data, and industrial clouds to develop online wear detection and diagnosis systems for cutting tools to ensure the high-quality and high-efficiency trimming of CFRPs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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