Research trends and future perspective in nonconventional machining of fiber-reinforced polymers: a review

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Abstract
This paper reports a comprehensive overview of nonconventional machining (NCM) of fiber-reinforced polymers (FRPs), which are widely used in high-tech industries owing to their superior mechanical properties compared with conventional metallic materials. To achieve FRP applications, hole processing for bolting and milling is required to match the dimensional precision. However, the large cutting force induced in conventional machining (CM), such as drilling and milling, causes severe failures, such as delamination and thermal damage to FRPs. To replace CM, various NCM technologies with efficient and powerful processing have been introduced to reduce FRP damage during machining. However, the complex nature of FRPs makes it difficult to identify the material removal mechanism and predict the machining quality and degradation of material properties. Not only the quantification of the machining parameter and performance but also an analysis to determine their relation is necessary. However, unlike many previous CM reviews, there are only a few reviews on NCM for FRPs. This paper addresses three types of representative NCMs: laser beam machining, rotary ultrasonic machining, and abrasive water jet machining. Each NCM is classified and systematically reviewed using a parametric study, mechanistic model, and numerical simulation. In addition, further studies on the NCM of FRPs are suggested.

1. Introduction

Composite materials have been widely applied in fields such as aerospace, automotive, and shipbuilding [1–3]. In contrast to conventional isotropic materials, composite materials, which are composed of two or more materials, exhibit distinct material properties, such as light weight, high damping, high specific strength, and favorable tribological behavior [4–7]. Fiber-reinforced polymers (FRPs) exhibit high strength by distributing the load into fiber reinforcements that have high tensile strength and stiffness [8, 9]. To assemble an FRP part with other parts, machining processes such as drilling and milling are usually conducted to create holes or fit the exact dimension after curing. During machining, critical failures, such as material degradation, occur frequently, which limits the FRP applications. Because many failure modes with complex machining mechanisms exist in FRPs compared with isotropic materials, a model that describes the machining phenomenon of FRPs is in high demand [10–12]. For instance, delamination, which is one of the most significant failures, can be caused by combining shear obtained from the rotation of the machining tool, cutting force in the through-thickness direction, and thermal residual stress [13–15].

For conventional machining (CM) methods, several studies on the relation between machining parameters and quality, such as cutting force and surface roughness (SR), have been conducted under isothermal conditions using various analytical techniques [16–18]. In addition, the thermal effect has been considered to analyze the degradation of mechanical properties owing to the low thermal conductivity of polymers [19, 20]. Besides parametric studies, mechanistic models that reflect the machining phenomenon
have been suggested and developed for three-dimensional finite-element (FE) models, including material removal [19, 21, 22]. However, the essential problems, such as delamination caused by the high cutting force and reduction in laminate thickness, high temperature due to the large difference in thermal properties of constituents, and excessive wear on the tool still exist, which lead to significant material degradation [23–27].

To overcome the essential problems of CM in FRPs, nonconventional machining (NCM) methods, such as laser beam machining (LBM), rotary ultrasonic machining (RUM), and abrasive water jet (AWJ) machining, have been developed. Singh et al reviewed the experimental results of RUM by introducing the effects of different variables on the machining quality [28]. Wang et al conducted a review on the damage induced on hard and brittle materials in RUM [29]. With the development of material removal mechanisms and cutting force models, damage formation and suppression were analyzed to easily access the machining phenomenon. Vigneshwaran et al reviewed AWJ machining with a focus on machining parameters, such as kerf and SR [30]. The effects of these parameters on the performance have been analyzed through numerous experimental studies. For example, Thakur et al performed a state-of-the-art review on the machining of FRPs with AWJ machining [31]. Starting from the mechanism of machining to optimization, an extensive literature survey has been systematically conducted. Although the reviews of individual NCM methods have already been conducted, they are not specified for FRPs or it is difficult to obtain an insight into selecting the appropriate NCM methods for FRPs.

A few reviews have included both CM and NCM. For example, Caggiano reviewed the machining of FRPs using both CM and NCM methods [32]. Several recent studies have introduced the key parameters and their influence on the machining performance. In addition, various methods for analyzing the present problems are briefly explained. By significantly lowering the cutting force compared to CM at the same removal rate, they concluded that RUM can be applied to FRP machining. Kumar et al reviewed the machining of carbon fiber reinforced polymers (CFRPs) and glass fiber reinforced polymers (GFRPs), especially for drilling [33]. The effects of tool materials and geometry were analyzed to improve the quality of the surface finish. For the NCM methods, each machining method was briefly reviewed both experimentally and analytically. Among the NCM methods, AWJ machining was investigated in detail. Using the same materials, Karatas et al reviewed the machinability of both CM and NCM [34]. The effects of the machining variables on the quality were investigated experimentally, and the relations among different parameters were analyzed using several analytical techniques. Owing to the increasing popularity of eco-friendly materials, Rajmohan et al analyzed the machining of natural fiber-reinforced composites [35]. The effects of machining parameters on the machining performance were investigated for both CM and NCM methods. Furthermore, several optimization techniques were used to obtain high machining quality. In contrast, various NCM methods were introduced briefly, not systematically. Antecedent reviews for the NCM methods are sufficient to notice the application of new technologies in FRP machining; however, it is difficult to systematically obtain information about each method, such as the effects of machining parameters on machining quality.

In this study, NCM methods, including LBM, RUM, and AWJ machining for FRPs, are introduced systematically. Motivated by the analysis of the CM method, each method is categorized into three steps: (a) parametric studies for the process variables by introducing various optimization methods; (b) mechanistic models to predict significant factors derived from the physics of the machining mechanism, such as the cutting force and temperature gradient; and (c) a numerical simulation to describe the machining phenomenon. Finally, directions for further studies for each NCM are suggested.

2. LBM

LBM is an effective advanced machining method for FRPs owing to its noncontact process, high speed, ease of automation, and accuracy [36–40]. The laser beam removes the material by melting and vaporizing the workpiece with a high heat flux, as shown in figure 1 [40, 41]. However, this thermal process incurs problems such as material degradation and low dimensional accuracy near the machined surface [42–44]. To analyze the machining performance, these problems are quantified by the heat-affected zone (HAZ), kerf width, and taper angle, as shown in figure 2 [39].

Many experimental studies have been conducted to minimize HAZ, kerf width, and taper angle by varying the LBM process parameters on composites with different fiber types and stacking sequences through various optimization techniques. In addition, many analytical models have been proposed to describe the machining phenomenon. In this section, the LBM of FRPs is reviewed through experimental and analytical studies. In addition, a numerical analysis is conducted to predict the mechanical damage and material removal rate (MRR) on the workpiece.
2.1. Parametric study

As mentioned above, the machining quality in LBM is quantified by the HAZ, kerf width, and taper angle. HAZ is a portion that has suffered from the degradation of mechanical properties because of being exposed to high temperatures and the kerf taper angle determines the dimensional accuracy of the products. Compared to dimensional accuracy, the degradation of the mechanical properties is more critical owing to the different thermal properties of the constituents; therefore, HAZ has been actively studied.

Depending on the type of machining, HAZ can be quantified using different methods. For drilling, Yung et al defined \( W_e \), a parameter of HAZ, as follows:

\[
W_e = \frac{A_1 + A_2}{L_1 + L_2}
\] (1)
where $A$ is the total section area of HAZ and $L$ is the length of the profile of the section hole, as shown in figure 3 [45]. Davim et al defined the method of quantifying HAZ in cutting, as shown in equation (2) [46]:

$$HAZ = \frac{Z_1 + Z_2 + Z_3}{3}$$

where $Z$ is the distance from the cut region to the end of HAZ at certain points [45]. Li et al suggested a new approach to characterize the thermal damage in FRPs by conducting a bearing fracture test [47]. The length of the fractured fiber can be regarded as HAZ because the load transfer is insufficient owing to the degradation of the matrix.

Studies on the relation between the machining parameters and quality have been conducted, in addition to the quantification of the machining quality. Caprino et al experimented with the LBM of FRPs by varying the reinforcements, power, and speed, and concluded that a high speed yields better quality under an appropriate power condition [37]. Similarly, Li et al argued that high speed is recommended because it prevents heat accumulation due to the short machining time [47]. In terms of power, Yung et al and Bluemel et al indicated that a low laser power is necessary to prevent HAZ growth because of the reduction in the accumulation of heat per time unit [45, 48]. Therefore, low laser power and high speed are generally recommended for high machining quality. In contrast, Herzog et al demonstrated the applicability of ultra-high power with high speed to machining CFRPs [49]. To avoid excessive heat during machining, a multipass strategy was adopted; however, some fissures and chipping were still observed. Nevertheless, these experiments have shown potential to reduce thermal damage caused to materials even with FRP machining using a high-power CW laser system.

Other parameters, such as laser impulse, auxiliary gas, and cutting directions, have also been investigated. Riveiro et al showed that HAZ and kerf width are mainly affected by the duty cycle in a pulsed laser, and that the taper angle exhibits linear relations with duty cycle, frequency, and pulse energy [39]. Raza et al also showed that a lower duty cycle provides the time for cooling, and thus, can prevent heat accumulation [50]. Additionally, Pan et al confirmed that the use of a cold nitrogen jet can effectively reduce HAZ by simultaneously cooling the machining temperature [51]. Furthermore, Riveiro et al experimentally investigated the effect of auxiliary gas pressure and the shape of the auxiliary gas outlet on the cuff width, taper angle, and HAZ in the pulsed mode [39]. The cutting direction is also an LBM parameter. Pan et al investigated the growth pattern of HAZ with respect to the fiber orientation [51].
direction was recommended to minimize HAZ growth, because of the removal of the degraded fiber. Li et al analyzed the effect of cutting direction on the laminates [47]. The edge of cutting was observed for two relative cutting directions, $0^\circ/90^\circ$ and $45^\circ/45^\circ$, where $45^\circ/45^\circ$ showed a better edge of cutting based on different heat conduction paths within the machining area.

Besides having established the relation between the parameters and quality, the LBM process has been optimized using various techniques. Rao et al performed process parameter optimization using the response surface methodology (RSM) and central composite design (CCD) based on the results of numerous CFRP cutting experiments conducted using a fiber laser [52]. Rivero et al performed laser parameter optimization by using a gray relation-based genetic algorithm for the experiments performed using a pulsed Nd:YAG laser for basalt fiber reinforced polymer cutting [39]. Tewari et al optimized the power and speed to minimize the kerf taper angle for kenaf/high-density polyethylene composites in laser drilling [53]. CCD was used to plan the experiments, and a regression model was developed for statistical testing to ensure the adequacy of the prediction. Finally, an analysis of variance (ANOVA) test was conducted on each experimental result.

### 2.2. Mechanistic model

To implement the LBM process with numerical analysis, mechanistic models that can describe the LBM mechanism are required. Although several studies have been conducted on the mechanical and thermal aspects, there is still no mechanistic model available that can accurately reflect the LBM process phenomenon. In mechanistic modeling, the temperature gradient in workpieces and the following thermal residual stresses are derived based on thermodynamics and solid mechanics. These mechanistic models provide the basic physics of material removal and the resultant defects in LBM.

#### 2.2.1. Thermal analysis

Material removal assumes that a material is completely decomposed if the weight loss is higher than 96% with increasing temperature [54, 55]. The weight losses were determined experimentally using thermogravimetric analysis. The complexity of the analysis originates from the high mismatch of thermal conductivity between the fibers and matrix, which affects the temperature distribution in a workpiece depending on the LBM conditions and material stacking sequence. Moreover, the heat capacities and decomposition temperatures of the constituents are different. Consequently, differences in the thermal properties of constituents degrade the mechanical properties and dimensional accuracy.

Therefore, the thermal analysis aims to develop a temperature distribution of the workpiece under laser irradiation. Negarestani et al used the governing equations of the transient thermal problem to obtain the temperature gradient in workpieces [54]. Using these heat equations, not only the HAZ dimensions but also the surface quality, such as fiber pull-out, could be predicted, because the model was considered heterogeneous. Furthermore, the temperature-dependent anisotropic thermal conductivity was used to simulate a more realistic CFRP model. This is because the thermal conductivity of CFRP decreases with less phonon–phonon scattering path in the carbon fibers as the temperature increases. Numerous studies have adopted this approach by considering LBM as a heat conduction problem.

Some studies have modified the heat equation to consider the effect of laser beam shape on heat distribution. Caprino et al formulated a simplified rectangular-Gaussian distribution to predict the laser beam power distribution in the direction of material thickness [56]. By combining the heat equation with Gaussian distribution, kerf can be predicted by calculating the width of the laser beam's entry and exit. Furthermore, the heat distribution can be calculated not only in the in-plane direction but also in the thickness direction. Tamrin et al modeled the heat source using Gaussian temporal and spatial profiles to describe a more realistic laser beam shape to predict the kerf width and heat distribution [57].

Additionally, the thermal conductivities with respect to the FRP orientation were considered. For simplicity, Li et al scaled down the model on a one-dimensional problem by assuming that heat conduction is always perpendicular to the laser beam path [58]. However, simulating complex cases, such as LBM on woven fabric or composites with complicated stacking sequences, is still difficult. To simulate composites with significantly anisotropic thermal properties, the thermal conductivities in all directions should be derived in case of machining in a non-principal direction. Pan et al evaluated the general anisotropic thermal conductivities from the principal thermal conductivities for unidirectional FRP by using the eigenvalue method and isotherm method [55]. In the eigenvalue method for calculating the principal thermal conductivities, the workpiece was assumed to be symmetric in the normal direction of the composite lamina. In the isotherm method for deriving the general anisotropic thermal conductivities from the principal thermal conductivities, HAZ was assumed to be elliptic and the ratio of the ellipse radii was equal to the square root of the ratio of the thermal conductivity in the radial direction.
2.2.2. Stress analysis

During the LBM process, the degradation of mechanical properties from interlaminar damage, such as delamination and cracking, can also occur due to thermal residual stress [59, 60]. Liu et al calculated the thermal stress induced by the temperature gradient to predict where the interlaminar damage likely occurs during laser beam irradiation [59]. Similarly, Tamrin et al developed a model that evaluates the variation in the elastic modulus and ultimate strength caused by thermal expansion and contraction under laser irradiation, to calculate the thermal residual stress [57]. Moreover, a connectivity matrix to develop the stress domain from the thermal domain was constructed to reduce the calculation time and error when the numerical simulation was conducted later. In addition, temperature-dependent Hashin failure criteria were formulated to obtain material removal with respect to strength loss at the ablation temperatures.

2.3. Numerical simulation

In the numerical simulation, material removal and damage caused on the material were predicted using the temperature distribution from the thermal analysis and stress distribution obtained from the stress analysis, respectively. In addition, the correlations between the machining performance and LBM conditions were explained.

Moghadasi et al developed an uncoupled thermomechanical FE model to simulate LBM on a carbon/Kevlar hybrid composite, as shown in figure 4 [61]. The numerical results for the HAZ and kerf width with respect to the fiber orientation and thermal conductivity agreed well with the experimental results, although a discontinuity existed in the temperature owing to the different thermal conductivities of the fibers. Tamrin et al also conducted an uncoupled thermo-mechanical FE model similar to the previous model for natural FRPs [57]. This model also showed suitable agreement with the experimental results, with an error of 9.1%. However, none of the studies simulated the mechanical damages, such as delamination and cracking, but only left the possibility that property degradation can accelerate the damage initiation.

Interlaminar cracking is a major type of mechanical damage caused by rapid temperature changes in LBM. Liu et al investigated the interlaminar damage of CFRP laminates under continuous-wave laser irradiation [59]. The technique for controlling the degrees of freedom (DOFs) was utilized to simulate cracking by decoupling the precoupled DOFs of the nodes at the interface in the laminate when the stress states satisfied the fracture criterion. The results showed that the maximum normal stress and shear stress occurred at the interfaces between the plies immediately after the laser beam was removed. Therefore, large interlaminar cracks appeared on the machined surface where the laser beam was already irradiated.

Negarestani et al developed a realistic three-dimensional FE model to observe the variation in the fiber pull-out and ablation depth with the scanning speed [54]. A heterogeneous fiber-matrix mesh was created to analyze the fiber pull-out caused by the difference in heat conductivities and deposition temperatures, as shown in figure 5. The results showed that both fiber pull-out and ablation depth decreased as the scanning...
speed increased, owing to the reduction in the interacting time. Although the tendencies of the change in fiber pull-out and ablation depth agreed well with the experimental results, the deviations between the two results of fiber pull-out were significant at a low scanning speed. This is attributable to the fact that some factors, such as beam scattering inside the cut surface and vapor formation, were assumed to be negligible.

Li et al developed thermal models to determine the influence of stacking sequences on HAZ size. There were three types of configurations: $+45/-45$, $0/90$, and plain woven with respect to the laser beam irradiation line. For simplicity, heat conduction was assumed to be unidirectional and perpendicular to the cutting direction. The simulation results showed that the HAZ of the composite with $0/90$ configuration was larger than that with $+45/-45$ configuration. This result reflects the relation between the HAZ and cutting direction with respect to the composite stacking sequences because the heat conduction in the fiber direction is much larger than that in the matrix.

Unlike the parametric studies, only a few studies have been conducted on the numerical simulations of other parameters such as auxiliary gas temperature, pressure, and laser pulse mode. Moreover, the prediction of HAZ with complicated configurations, such as plain-woven composites, remains challenging. Therefore, to understand and determine the real LBM mechanisms, more detailed parameters should be included in the numerical simulation.

3. RUM

Ultrasonic machining (UM) is an NCM with a low MRR; however, it can machine all materials, including brittle and nonconductive materials. The vibration with a high frequency of cutting tools causes the abrasive particles in the slurry to impact the workpiece, inducing machining by microchipping. RUM, a combination of conventional rotary machining and UM, can effectively improve the MRR compared to the conventional ones because of the additional material removal mode, as shown in figure 6. This mode lowers the cutting force at the same MRR, and thus, is highly applicable to the machining of FRPs, including both brittle and ductile materials, to prevent delamination.

Recently, RUM has been extensively studied, from parametric studies to the application of new technologies such as elliptical RUM. In this section, the effects of input variables, such as the feed rate, spindle speed, depth of cut, amplitude, frequency, coolant pressure, ultrasonic power, and grit size, on the machining performance, including the delamination and surface quality, are analyzed as shown in figure 7. First, parametric studies are introduced with various models to explain the relation between the process parameters. Then, an analytical model is used to investigate the fracture mechanics with the equivalent mechanical properties of the composite. Finally, a numerical analysis is conducted to explain the formation of edge chipping and the phenomenon of delamination during machining.
3.1. Parametric study
In RUM, only a few parametric studies have been conducting on FRP machining. Instead, many mechanistic approaches for predicting parameters such as MRR and cutting force have been studied and verified experimentally. Even though the mechanistic model predicts a certain parameter exactly, it is still difficult to predict other parameters that are difficult to quantify, such as surface morphologies. In this section, the
parametric studies conducted for ceramic materials and a few FRPs are introduced with various methods to motivate further studies on FRP machining.

Hu et al studied the interaction between the input variables and MRR with a five-factor two-level factorial design and concluded that cutting force had the most significant effect on MRR [70]. Li et al also used a three-variable two-level full factorial design to obtain the two-factor interaction of feed rate, spindle speed, and ultrasonic vibration and showed that the cutting force was reduced effectively and was significantly affected by the feed rate [71]. In addition, the hole quality was highly dependent on the spindle and feed rate. Ning et al analyzed the effects of process variables on the cutting force through a five-variable two-level full factorial design by using a mechanistic model for CFRPs [72]. The feed rate was the most significant input variable, and the combination of vibration amplitude and abrasive concentration showed the lowest interaction.

In addition, other methods have also been proposed to determine the relation between the input parameters and machining performance. A data-dependent system that identifies the differential/difference model with or without conjecturing the corresponding form was proposed by Wu et al [73]. The relation between the wavelength to feed rate and the grain size of the workpiece material was evaluated by the data-dependent system wavelength decomposition. Abdo et al used the Taguchi optimization methodology to determine the relation between the cutting force and MRR with different factors [74]. Recently, to minimize SR and edge chipping, Abdo et al used a multiobjective genetic algorithm [75]. The model yielded low levels of feed rate, cutting speed, and depth of cut, and high levels of amplitude and frequency were recommended as the optimal conditions.

3.2. Mechanistic model
In the mechanistic model, the MRR and cutting force were derived analytically in terms of the fracture mechanics. In particular, the cutting force is highly related to FRP delamination [76]; therefore, a mechanistic model to predict the cutting force with high accuracy is required. In this section, two types of machining, drilling and grinding, are modeled based on the different directions of the cutting force.

3.2.1. Drilling
Pei et al proposed a mechanistic model to predict the MRR for a brittle material [66]. By estimating the indentation depth and cutting force while tracking the path of abrasive particles, MRR was formulated assuming that the removal volume was identical to the indented volume. However, the actual removal volume must be larger than the indented volume owing to the crack formation. Liu et al modified the removal volume by considering the crack formation induced by the indentation of the abrasive particles, as shown in figure 8 [77]. The crack length was calculated by comparing the stress intensity factor induced by the contact force with the fracture toughness of the workpiece. Cong et al applied the same approach to CFRPs to predict MRR [78]. In this model, the equivalent homogeneous mechanical properties were used to estimate the indentation depth and the equivalent fracture toughness with respect to the orientation was
derived to calculate the removal volume by using the rule of the mixture. As a result, the MRR predicted by the model was highly comparable to the that evaluated experimentally.

Although the proposed mechanistic model predicted the MRR and cutting force with high accuracy, the fracture volume factor, which is the ratio of the theoretical volume and actual fractured volume of a material, should be obtained experimentally. This is attributed to the difficulties in accurately predicting the crack length and the assumption that all abrasive particles participated in machining. The equivalent fracture toughness based on micromechanics was used in FRP as an isotropic material, such as ceramic. In this case, both the retardation of the crack propagation by fibers (figure 9) and the variation in the fracture toughness with respect to the interface ply orientation and delamination growth direction cannot be considered in the present model [79, 80]. Therefore, the fractured volume formed by indentation may be unmatched in a real situation. In the future, estimating the fractured zone for FRPs is required.
3.2.2. Grinding
Liu et al. developed a mechanistic model for the MRR and grinding force in the feeding direction of CFRPs on rotary ultrasonic face grinding [81]. First, the motion of the abrasive particles was analyzed to quantify the fractured region. Then, the MRR and cutting force were derived based on the micromechanics of the composite and fracture mechanics. Ning et al. constructed a mechanistic model using the same procedure [82]. The difference lied in the procedure used to derive the crack length induced by the indentation. Ning et al. obtained the lateral crack depth related to the indentation depth, whereas Liu et al. expressed the cutting force with the indentation depth and hardness of the workpiece. In addition, the model was validated experimentally, and it was determined that the model fitted well with the experimental results. However, the exact fracture volume was not evaluated analytically.

Recently, RUM with elliptical UM has been proven effective in terms of surface quality and reduction of the cutting force [83]. Cong et al. added the horizontal ultrasonic vibration of the tool to a previous study to implement elliptical UM [84]. First, the effective trajectory length of abrasive particles and the cutting time during the grain–workpiece interaction were modified based on the MRR. Then, the effect of the amplitude of horizontal vibration on the cutting force was identified by analyzing the indentation depth and contact time. Finally, an experiment was conducted to verify the model, which showed a suitable prediction of the cutting forces under different conditions.

3.3. Numerical simulation
Although the mechanistic model predicts the cutting force and MRR with high accuracy, it is difficult to determine the relation between the machining parameters and mechanical damages. This section introduces numerical models by using the FE method to identify failures in the workpiece. Similar to the parametric studies, the numerical model for the ceramic material was first introduced, followed by the model for FRPs, especially CFRPs.

To analyze the formation of edge chipping in ceramics, Zhichao et al. modeled a ceramic workpiece with finite elements [85]. The cutting force varied linearly in the filet zone, as shown in equation (3),

\[
F_{\text{cutting}} = \begin{cases} 
14.8 \left(1 + \frac{x}{r}\right), & -\frac{l}{2} \leq x \leq -\frac{l}{2} + r \\
7.4, & -\frac{l}{2} \leq x \leq -\frac{l}{2} + r \\
14.8 \left(1 - \frac{x}{r}\right), & \frac{l}{2} - r \leq x \leq \frac{l}{2} 
\end{cases} 
\]  

(3)

where \(r\) is the fillet radius and \(l\) is the width of the flat portion of the cutting zone. The results showed that critical stress concentration occurred in the filet zone. The shape of the edge chipping was predicted to well-match with the stress contour. However, the exact contour could not be obtained because the stresses were a function of the fillet radius.

Unlike homogeneous ceramic materials, the dominant failure mode for FRPs is delamination. Cong et al. conducted an FE analysis to determine the delamination in the RUM of CFRPs, especially push-out delamination [86]. The workpiece was modeled with stacks of orthotropic lamina, and cohesive elements were used at their interface, where the delamination was dominant. Under the static cutting force based on preliminary experiments, delamination procedures were performed. The simulation results were divided into four steps with respect to the separation between the adjacent layers of the cohesive elements, and each step agreed with the experimental results. Moreover, the relation between the delamination thickness and cutting forces was derived, and a larger cutting force was found to result in a large delamination thickness owing to an increase in bending stiffness. When comparing the numerical results with the experimental results, a larger cutting force was obtained at a certain delamination thickness. There are two possible reasons for this finding. First, the properties of cohesive elements are not accurate. Second, in reality, delamination can occur from the combination of sliding, tearing, and opening failure modes, even though the opening mode is dominant. Another reason can be the underestimation of the stress exerted on the cohesive element. In the numerical analysis, the cohesive elements were located between two flat surfaces; however, the delamination occurred at the fiber–matrix interface, and thus, the stress concentration due to the interface geometry should be reflected. Then, a lower force is sufficient to initiate delamination at the interface. Thus, it is reasonable to observe the delamination area from the experiment as shown in figure 10 [87]. The boundary of the delamination fluctuated because of the uneven stress field induced at the interface. Therefore, a microscale modeling that has two phases, fibers and matrix, is recommended for further studies.
4. AWJ machining

Water jet (WJ) is another representative NCM method that uses pressurized water and has advantages such as cold cutting without contact between the tool and workpiece, eco-friendly process, high precision, and low material loss [88, 89]. AWJ machining is a type of WJ specialized in the cutting, drilling, and milling of brittle materials. Unlike pure WJ, which is usually applied to ductile materials, AWJ machining is appropriate for brittle materials because of an additional erosion effect induced by mixing dry or wet abrasives with pressurized water and colliding abrasive particles on the workpiece at high speed, as shown in figure 11 [90]. The microcutting of a workpiece by abrasive particles is a fundamental event in the material removal mechanism of AWJ machining. Therefore, AWJ, which can process more powerfully and rapidly, is suitable for brittle materials, such as ceramics, metals, and composites [91–93]. In particular, machining CFRPs using AWJ is an active research field in high-tech industries, such as aerospace and automobiles [94]. Although AWJ has many advantages, delamination, SR, and kerf taper after FRP machining remains challenging [95–97]. The nature of composites, which have inhomogeneous properties and weak interfaces, increases the complexity of the analysis [69, 92]. Therefore, researchers have focused on the reduction and prediction of FRP damage caused by AWJ.

In this section, studies on AWJ machining of FRPs are classified with respect to their methodology in terms of experimental and theoretical aspects. First, various process parameters and optimization methods are introduced in a parametric study, and then, their influence on the machining performance is examined. Next, analytical studies that have established and verified a mechanistic model focusing on the energy approach are reviewed. Finally, a numerical analysis for predicting delamination and the AWJ machining mechanism is conducted.
4.1. Parametric study
Parametric studies based on experiments have taken the mainstream of conventional research because of the various machining parameters and insufficient understanding of the AWJ machining mechanism of inhomogeneous FRPs. As shown in figure 7, the AWJ process parameters are classified as follows: hydraulic, abrasive, mixing, and cutting parameters. Among these, the jet pressure, transverse rate, abrasive type and size, and standoff distance are considered as representative process parameters [98]. The machining quality varies according to the combination of the process parameters and can be evaluated from the SR, taper geometry, and MRR [69].

Unlike cutting, AWJ drilling and milling have rarely been studied [93, 94, 99–101]. However, because hole creation and secondary machining for assembly and exact dimensions primarily occur in the range of applications with FRPs, other types of machining should be analyzed as much as cutting. For this purpose, the methodology of parametric study for AWJ cutting can be applied as it is and the process parameters, such as hole diameter and milling depth, can be added or excluded according to the machining type [102]. In addition, various methodologies have been used to optimize the process parameter levels, of which the Taguchi method and ANOVA are the most commonly used [102–104]. RSM is another approach for obtaining a multiple linear regression model [105]. Recently, artificial intelligence technology has been applied as a statistical technique [106, 107].

The effect of process parameters on the mechanical properties of the composites after machining is also of interest. Initially, SR was considered the dominant factor in the mechanical properties of FRPs, which was adopted from the studies conducted using the AWJ of brittle materials such as ceramic [108–110]. However, Ramulu et al and Ghidossi et al, respectively, reported that the compressive strength of graphite/epoxy composite and tensile strength of GFRPs are not relevant to SR [111, 112]. A mismatch between the SR and mechanical properties is not a problem incurred by AWJ machining alone; other studies have also revealed that the machining quality and mechanical performance of FRPs cannot be judged with SR [108, 113, 114].
Recently, Hejjaji et al claimed that the SR of AWJ-machined FRPs cannot represent the machined quality, unlike conventional metal materials [94]. Instead, the crater in figure 12, which is a representative form of damage occurring in the AWJ processing of FRPs, dominates the mechanical properties of the workpiece. They conducted a tensile test on CFRP specimens processed by AWJ milling and confirmed that the smaller the total crater volume on the machined surface, the higher are the tensile strength and stiffness. Hejjaji et al highlighted the importance of crater volume by studying the fatigue behavior of CFRPs milled using AWJ [115]. Nguyen-Dinh et al suggested that the crater volume and maximum depth of damage are indicators of the mechanical properties of AWJ-trimmed CFRPs [116].

In summary, the parametric study of AWJ machining of composite materials focused on the correlation of machining quality according to the process parameters and the relation between machining quality and mechanical properties of the workpiece. Owing to the diversity of the process parameters and the complexity of composites, parametric studies are the easiest and most effective approach so far. However, this approach is only applicable to certain machining conditions and materials and lacks extensibility. Therefore, big data technology, which can use the contribution of each variable to the output parameters based on the database of dominant process parameters and their levels for various composite materials and machining methods, holds promise for future study.

4.2. Mechanistic model

Owing to the complexity of AWJ, mechanistic modeling has not been actively addressed and is limited to specific materials or processing conditions. Ho-Cheng conducted a feasibility study on WJ machining of FRPs based on fracture mechanics [117]. Subsequent studies have also been conducted to construct a mechanistic model using an energy approach. However, these are highly dependent on the empirical approach, and thus, there is no complete mechanistic model available yet. Nevertheless, the influence of each process parameter and material characteristic on the machining quality can be roughly understood using a mechanistic model.

Ho-Cheng et al studied the AWJ milling characteristics of CFRPs and obtained the relations between significant process parameters and machining quality [100]. The volume removal rate, depth of cut, width of
cut, and width-to-depth ratio were derived from a dimensional analysis conducted using the Buckingham PI theorem. The predicted output values agreed well with the experimental results. In addition, Wang et al proposed a semi-empirical model for determining the penetration depth required to prevent delamination that occurs when the penetration depth is insufficient because of the low kinetic energy of the jet [118]. An energy approach was applied, and an analytical model was compared with the AWJ cutting data of CFRP composites. Shanmugam et al presented a mathematical model to measure the maximum delamination length by using an energy approach, linear elastic fracture mechanics, and dimensional analysis [95]. Thongkaew et al predicted the maximum machining error of the hole diameter after AWJ hole drilling and hole cutting of CFRPs [119]. This study determined the programmed diameter and selected an appropriate machining method according to the desired hole diameter. They also dealt with the chipping mechanism on the AWJ-machined surface of CFRPs. The top surface of the workpiece was subjected to hydraulic impact and had round corners and chips. In case of drilling, the laminate of the bottom surface was subjected to bending force; therefore, chips were generated. Sourd et al proposed two models of the depth of cut in AWJ milling of CFRPs by using pocket depth measurements and the algebraic sum of elementary passes [120].

The results of all previously introduced studies tended to agree with the experimental data, which can significantly contribute to this research field. However, as they were semiempirical models derived in terms of the selected process parameters, the physical properties and reinforcement types of FRPs were not appropriately reflected. Several studies have included Young’s modulus in their formula; however, it shows a clear limitation in applying the mechanistic model to various composites. In the future, the dominant material characteristics in machining need to be clarified and a database that can mathematically or empirically apply the effect of the material characteristics to the mechanistic models should be established.

4.3. Numerical simulation

Although the construction of the mechanistic model focuses on fitting the results of machining and damage, the numerical model can describe the machining phenomenon as well. Recently, computational simulations of coupled fluid-structure domains have been conducted using computational fluid dynamics and the FE method.

Schwartzentruber et al used a one-way fluid–structure interaction (FSI) model to simulate AWJ cutting of CFRPs [121], where a cohesive element zone was applied in the structural domain to predict the workpiece
delamination. They concluded that the delamination was mainly attributed to the loading on the cutting front. This result was confirmed using a micro-computed tomography (CT) image of the crack ahead of the cutting front. This group further advanced the previous study to predict CFRP delamination in AWJ piercing by using a two-way FSI model, as shown in figure 13 [122]. They described the delamination induced at the top surface by hydraulic shock. Nyaboro et al studied the AWJ drilling of CFRPs by using a two-way FSI model to investigate the delamination mechanism and hole geometry [123]. A high jet velocity or jet power increased the debonding area caused by delamination. They also demonstrated the simultaneous occurrence of the brittle mode fracture and ductile mode fracture.

The above studies revealed that delamination in the early stage of machining is caused by the hydraulic impact of the jet. However, the accuracy of the simulation is still insufficient because of the complex anisotropic nature of composites, various machining methods and process parameters, and insufficient understanding of the mechanism that causes the damage. In the future, the exact fracture mode and mechanism must be investigated using both a multiscale and a macroscale approach.

5. Conclusions

This paper provides a systematic review of the three most remarkable NCM methods for FRPs: LBM, RUM, and AWJ machining. Each machining method was analyzed in the following order: parametric study, mechanistic model, and numerical simulation. From the reviews above, the following conclusions and directions for further studies are drawn.

(a) Most studies have presented the relation between the input parameters and machining quality in LBM. Based on the parametric studies, the optimal input parameters were derived using advanced techniques. Then, a mechanistic model was developed to analyze the material removal mechanism. However, only a small portion of the workpiece was modeled, owing to the limited computational time; thus, it is difficult to represent the entire system exactly. However, the selection of appropriate size of the modeling domain showed high compatibility with the experimental result. Furthermore, other factors, such as vapor formation and laser beam scattering, should be considered to achieve higher accuracy.

(b) In RUM, parametric studies for ceramics with various optimization techniques were conducted to motivate further studies on FRPs. Then, mechanistic models for drilling and grinding were introduced. The fractured volume was modeled with respect to the indentation of the abrasive particles; however, it was still modified by the fractured volume factor derived from the experiments. In the FE analysis, the delamination procedures were described by modeling the interface with the cohesive elements. However, with an appropriate damage criterion, dynamic load, and presence of abrasive particles on the tool, the fracture phenomenon on the workpiece should be modeled to reflect the real machining process.

(c) AWJ has been studied mainly for parametric studies owing to the diversity of process parameters and complex relations. Recently, advanced technologies, such as big data analysis, as well as the Taguchi method and ANOVA, have been used. In addition, mechanistic models derived by the energy approach and numerical models using the FSI model to predict the machining performance, such as delamination and kerf geometry, have been proposed. However, the models are limited to specific materials and machining conditions because of their high dependence on the experimental results. To achieve a high machining quality, appropriate levels of machining parameters should be chosen through micro- and macroscale modeling, including the interaction between composites and abrasive particles under the exact machining mechanism.

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