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Numerical prediction of the chip formation and damage response in CFRP cutting with a novel strain rate based material model

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Abstract

Carbon fibre reinforced plastics (CFRPs) are susceptible to various cutting damages. An accurate model that could efficiently predict the material removal and chip formation mechanisms will thus help to reduce the damages during cutting and further improved machining quality can be pursued. In previous studies, macro numerical models have been proposed to predict the orthogonal cutting of the CFRP laminates with subsurface damages under quasi-static loading conditions. However, the strain rate effect on the material behaviours has rarely been considered in the material modelling process, which would lead to the inaccurate prediction of the cutting process and damage extent, especially at high cutting speed. To address this issue, a novel material failure model is developed in this work by incorporating the strain rate effect across the damage initiation (combined Hashin and Puck laws) and evolution criteria. The variation in material properties with the strain rate is considered for the characterization of the stress-strain relationships under different loading speeds. With this material model, a three-dimensional macro numerical model is established to simulate the orthogonal cutting of CFRPs with four typical fibre orientations. The machining process and cutting force simulated by the proposed model are well agreed with the results of the CFRP orthogonal cutting experiments, and the prediction accuracy has been improved compared with the model without considering the strain rate effect. In addition, the effects of processing conditions on the subsurface damage in machining 135° fibre orientation CFRPs are assessed. The subsurface damage is found to decrease with the rise of cutting speed until 100 mm/s, afterwards, it tends to be stable when the cutting speed is over 100 mm/s. The increased severity of the subsurface damage is predicted with the higher cutting depths.

Keywords: CFRP; Cutting; Simulation; Damage; Strain rate; Material model

1 Introduction

Carbon fibre reinforced plastics (CFRPs) have become a favourable material for high-end equipment in the aerospace, transportation and energy sectors. Their extraordinary properties, for example, high specific strength, high specific modulus, corrosion and wear resistance are suitable for the performance enhancement and weight reduction of the components [1-3]. The CFRP parts are mostly manufactured with near-net-shapes by autoclave or resin transfer moulding (RTM) approaches [4]. However, for meeting the strict tolerance on dimension and high surface quality requirements of the components during the assembly, the secondary machining processes, such as drilling and edge trimming, are always necessary and in great demand [5-8]. Unfortunately, CFRP is a typical hard-to-machine material and severe damages frequently occur around the processed area [9-11]. These damages, for instance, fibre pull-out, matrix cracking and delamination, could significantly degrade the bearing capacity and shorten the service life of the whole components, and the burrs would result in serious assembly errors and even lead to part rejection [12-16]. Therefore, in-depth analysis of the material removal and chip formation mechanisms in the CFRP machining, and further to minimise the damages by optimising the tool geometries and processing parameters, are urgently required.

However, during the drilling or milling processes of CFRPs, there exist complicated contacts between the tool and the workpiece. In the through-thickness direction of the laminates, the cutting edges, rake faces, etc. of the tool simultaneously act on the CFRP layers laminated with various fibre orientations, and the fibre cutting angles (the angle measured clockwise from the cutting direction of the cutting edge to the fibre orientation [17]) for each layer are different [18]. Additionally, with regard to the cutting on any layer of the workpiece, the fibre cutting angle cyclically changes with the rotation of the drill bit or mill cutter. Therefore, the material removal of CFRPs is hard to be revealed by analysing the drilling or milling processes, because several factors such as fibre orientation and cutter structures and their interactions would be involved in one trial together. To address this issue, a simple cutting operation should be adopted, and the orthogonal cutting of the unidirectional CFRPs under various fibre cutting angles is preferred in the investigation.

Currently, orthogonal cutting experiments have been conducted to explore the machining mechanism of the unidirectional composites [19-22]. The changes in the chip morphology, surface roughness and subsurface damage with the fibre cutting angle, tool rake angle and cutting depth were experimentally evaluated. However, the local failure and removal processes of the composites are still not clear enough, although great efforts have been done in the CFRP cutting observation and the most advanced high-speed and high-resolution cameras were adopted [19, 21, 22]. Moreover, when assessing the influences of the tool geometries and processing parameters on the material removal and damage formation by experiments, abundant composites and tremendous amounts of tests are demanded, which results in high cost and waste, and low efficiency. By contrast, finite element (FE) simulation is capable of visualising the interaction between the tool and the workpiece at desired geometrical scale and position, and predicting the initiation and development of damage or defects under various loading conditions [23, 24]. Furthermore, the optimization of the tool geometries and machining parameters could be achieved by just revising the processing conditions of the FE model, and detailed interesting outputs will be obtained within one simulation. That would potentially save the huge time and cost on material manufacturing, processing and testing, avoiding any wastes produced during experiments. Therefore, the numerical simulation of the CFRP orthogonal cutting has been widely carried out to research the chip and damage formation.

To understand the details of material removal of CFRPs during the cutting process, both micro and macro models have been developed [25-29]. Wherein, the micro model could be used to analyse the tool action on the component phases and the interaction and fracture of these phases. However, the complex material and geometric models should be defined for the individual fibres, matrix and interfaces in a microscopic simulation, and the computational cost is quite expensive. In this case, an equivalent homogeneous material (EHM) macro model with less calculation time needed was widely employed. Santiuste et al. [30] proposed a two-dimensional (2D) plane stress model to simulate the composite processing under 0.5 m/min cutting speed where the workpiece was considered as an EHM and the CFRPs were defined with elastic anisotropy behaviour up to failure. Meanwhile, the 2D Hashin criteria were adopted to determine the progressive initiation of the various damage modes, and thus to assess the influences of the fibre orientation on the chip formation mechanism and subsurface damage. Based on the maximum stress and Puck criteria, Cepero-Mejías et al. [25] numerically evaluated the machining induced damage within the composite by a 2D macroscopic model. In their work, unidirectional CFRPs with different fibre orientations were cut under various tool geometries and a constant cutting speed of 8.33 mm/s. The simulation results explained the changes of the in-plane damage with the processing conditions, and pointed out that a suppressed damage could be caused by a decreased fibre orientation and an increased clearance angle. In order to acquire more detailed subsurface damage outcomes from the three-dimensional (3D) perspective, Santiuste et al. [4] developed a 3D FE model for the CFRP orthogonal cutting on the macro scale. Depending on this model, the damage fields in the machining of unidirectional and multidirectional CFRPs were displayed. Such studies have generally reported and analysed the in-plane and out-of-plane damages caused during the CFRP machining under relatively low cutting speed.

However, the cutting speed could exceed 1 m/s, even reach 5 m/s, in a realistic CFRP trimming or drilling process [18, 31, 32]. It is known that the material properties of CFRP laminates are strain rate dependent [33-36], while the strain rate at which materials are loaded ranges from 10^{-5} s^{-1} in quasi-static loading to 10^{6} s^{-1} in high-speed cutting [37, 38]. Therefore, the material removal process and damage extent would be different when machining CFRPs using various cutting speeds. Under this circumstance, the strain rate effect should be involved in the CFRP failure simulation and damage assessment, otherwise, results with great errors would be obtained. In this field, some related investigations could have been hence found to develop constitutive models and failure criteria that consider strain rate effect [33, 39-41], and to predict the dynamic fracture and damage of CFRPs under uniaxial, multiaxial and impact loads [36, 42-45]. However, a study in terms of CFRP processing with more intensive loading applied, such as cutting, has rarely been reported.

The main objective of this paper is to analyse the chip formation mechanism and damage response in the machining of CFRP laminates under various processing conditions. To this aim, a novel material failure model is developed with the strain rate embedded into the damage initiation principle which is based on the Hashin and Puck criteria, as well as the damage evolution laws based on the continuum damage mechanics (CDM). The change in CFRP properties with the strain rate is incorporated for the characterization of the stress-strain relationships under various loading speeds. Based on this material model, the orthogonal cutting of unidirectional CFRPs with four typical fibre orientations is modelled by developing a 3D FE model on the macro scale, and the effects of the tool rake angle, cutting speed and cutting depth on the subsurface damage are figured out. In addition, experiments with cutting process recording are conducted to validate the numerical model. With the outcomes obtained from the modelling and experiments, the optimised operational parameters during the cutting process could be given for minimising the damage.

2 Numerical model

In the first part of this section, the proposed progressive damage model for the composite material is comprehensively explained. Then, details of the FE model including the geometric model and boundary conditions are introduced.

2.1 Progressive damage model of the composite material

The workpiece in this study is fabricated by the P2352 prepregs, which consists of the T800S fibres and 3900-2B epoxy resin (Toray Ltd, Japan). During the cutting process, the material fractures after the increase of stresses and the initiation and evolvement of the various damage modes. The developed material model in this work hence includes both damage initiation criteria and damage evolution laws defined for the individual damage modes of the composite for an accurate prediction of the CFRP cutting process. In addition, the strain rate effect on the machining responses of CFRP laminates is taken into account to be embedded in the composite damage model.

2.1.1 Constitutive model and damage initiation criteria

The composite workpiece is assumed as EHM with orthogonal anisotropic features where the stress-strain relationship with damage evolution could be expressed by Fig. 1.

To characterise the material behaviour of CFRPs prior to damage, the linear elastic constitutive model is defined by Eq. 1. Where ε_i and γ_{ij} are the normal and shear strains, respectively; and σ_i and τ_{ij} are the normal and shear stresses, respectively. E_i and G_{ij} represent the elastic and shear moduli, respectively; and v_{ij} denotes Poisson's ratio. Here, i, j = 1, 2, 3; and 1, 2 and 3 are the longitudinal direction, transverse direction and through-thickness direction of the laminates, respectively.

$$\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\\ \gamma_{12}\\ \gamma_{13}\\ \gamma_{23}\end{bmatrix}=\begin{bmatrix}\frac{1}{E_1} & \frac{-\upsilon_{21}}{E_2} & \frac{-\upsilon_{31}}{E_3} & 0 & 0 & 0\\ \frac{-\upsilon_{12}}{E_1} & \frac{1}{E_2} & \frac{-\upsilon_{32}}{E_3} & 0 & 0 & 0\\ \frac{-\upsilon_{13}}{E_1} & \frac{-\upsilon_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1}{G_{12}} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{23}}\end{bmatrix}\begin{bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \tau_{12}\\ \tau_{13}\\ \tau_{23}\end{bmatrix} \tag{1}$$

Because of the orthotropic and inhomogeneous features of CFRPs, various damage modes would occur in the workpiece under the cutting loads applied, such as fibre fracture, matrix cracking, etc. [9]. Hashin criteria [46, 47] are able to model four distinct failure modes: fibre tensile failure, fibre compressive failure, matrix tensile failure, and matrix compressive failure. Therefore, they have been extensively utilised to predict the damage initiation for composites [17, 48, 49]. However, it was found that Hashin criteria cannot accurately simulate the matrix compressive failure initiation [23, 50]. To address this issue, our previous studies [23, 24] have combined the Puck's law with Hashin together for numerical simulation of low velocity impact testing, which showed the successful prediction for the individual damages of composite with the good agreement with experimental measurements. Therefore, this approach is applied in the present research to simulate the cutting process of CFRP laminates. More specifically, Hashin criteria are selected to determine the tensile damage initiation and fibre compressive failure, while a criterion based on the theory of Puck [51, 52] is adopted to estimate the matrix compressive failure, as illustrated in Table 1. Where F is the failure index. The superscripts T and C indicate the tensile and compressive failure, respectively; the subscripts f and m express the fibre and matrix failure, respectively. X^T and X^C denote the tensile and compressive strengths of the unidirectional CFRPs in the longitudinal direction while Y^T is the tensile strength in the transverse direction. S_{ij} is the corresponding shear strength.

According to the investigations of Puck et al. [51-53], the unidirectional composites are usually fractured along a plane with an angle of θ to the through-thickness direction under compression loading in the transverse direction, as shown in Fig. 2. σ_{nn}, τ_{nt} and τ_{nl} are the traction stress components in the normal, transverse and longitudinal directions on the fracture plane, respectively. They are obtained from the components of the stress tensor and the fracture plane angle θ:

$$\begin{aligned} \sigma_{nn} &= \sigma_2 \cos^2\theta + \sigma_3 \sin^2\theta + 2\tau_{23} \sin\theta \cos\theta \\ \tau_{nt} &= \left(\sigma_3 - \sigma_2\right) \sin\theta \cos\theta + \tau_{23} (\cos^2\theta - \sin^2\theta) \\ \tau_{nl} &= \tau_{31} \sin\theta + \tau_{21} \cos\theta \end{aligned} \tag{2}$$

S_{23}^A is the shear strength in the fracture plane, which can be expressed as [54]:

$$S_{23}^A = \frac{Y^C}{2\tan(\theta)} \tag{3}$$

Y^C is the compressive strength in the transverse direction. μ_{nt} and μ_{nl} are the friction coefficients, and they are defined as [54]:

$$\mu_{nt} = -\frac{1}{\tan(2\theta)}, \quad \mu_{nl} = S_{12} \frac{\mu_{nt}}{S_{23}^A} \tag{4}$$

2.1.2 Damage evolution laws

Since the individual damage has been initiated, the material stiffness of CFRPs starts to degrade with the irreversible evolution of damage under the external cutting loads. In this research, a CDM based evolution law is applied for the individual failure mode while the related stiffness is progressively degraded with the evolved damage factor d, as illustrated in Fig. 1. The damage factor d is defined based on the strains, including the strain variable ε at each time step, and the damage onset strain ε^0 and complete failure strain ε^f (see Eq. 5). The damage factor, *d*, is obviously 0 at the onset of failure and could reach the value of 1 once it is completely failed. In each time step after damage initiation, the relevant effective stress components are multiplied by (1 - *d*). This way, the damaged stress components are progressively decreased to zero with the increase of ε.

$$d = \frac{\varepsilon^f(\varepsilon - \varepsilon^0)}{\varepsilon(\varepsilon^f - \varepsilon^0)} \tag{5}$$

To be specific, the damage factors for fibre tensile (d_f^T), fibre compressive (d_f^C) and matrix tensile (d_m^T) failure modes are:

$$d_f^T = \frac{\varepsilon_1^{fT}(\varepsilon_1 - \varepsilon_1^{0T})}{\varepsilon_1(\varepsilon_1^{fT} - \varepsilon_1^{0T})},\ d_f^C = \frac{\varepsilon_1^{fC}(\varepsilon_1 - \varepsilon_1^{0C})}{\varepsilon_1(\varepsilon_1^{fC} - \varepsilon_1^{0C})},\ d_m^T = \frac{\varepsilon_2^{fT}(\varepsilon_2 - \varepsilon_2^{0T})}{\varepsilon_2(\varepsilon_2^{fT} - \varepsilon_2^{0T})} \tag{6}$$

Where the damage onset strains (ε_1^{0T}, ε_1^{0C} and ε_2^{0T}) are given by Eq. 7, and the final failure strains (ε_1^{fT}, ε_1^{fC} and ε_2^{fT}) are formulated by Eq. 8:

$$\varepsilon_1^{0T} = \frac{X^T}{E_1},\ \varepsilon_1^{0C} = \frac{X^C}{E_1},\ \varepsilon_2^{0T} = \frac{Y^T}{E_2} \tag{7}$$

$$\varepsilon_1^{fT} = \frac{2G_{1C}^T}{X^T L^c},\ \varepsilon_1^{fC} = \frac{2G_{1C}^C}{X^C L^c},\ \varepsilon_2^{fT} = \frac{2G_{2C}^T}{Y^T L^c} \tag{8}$$

Where G_{1C}^T, G_{1C}^C and G_{2C}^T denote the fracture toughness associated with these three generic failure modes, respectively. L^c is the characteristic length of the elements, and it is introduced to reduce the mesh dependency of the simulation results [23].

While for the compressive failure in the transverse direction, the damage factor is defined by the strain acting on the fracture plane:

$$d_m^C = \frac{\varepsilon_{mat}^{fC}(\varepsilon_{mat} - \varepsilon_{mat}^{0C})}{\varepsilon_{mat}(\varepsilon_{mat}^{fC} - \varepsilon_{mat}^{0C})} \tag{9}$$

Where $\varepsilon_{mat} = \sqrt{\langle \varepsilon_{nn} \rangle^2 + \gamma_{nt}^2 + \gamma_{nl}^2}$. The symbol $\langle \bullet \rangle$ indicates that, for any real number *x*, $\langle x \rangle = \left(x + |x|\right)/2$. The strain components in the fracture plane are expressed as:

$$\begin{aligned} \varepsilon_{nn} &= \varepsilon_2 \cos^2\theta + \varepsilon_3 \sin^2\theta + \gamma_{23}\sin\theta\cos\theta \\ \gamma_{nt} &= 2\left(\varepsilon_3 - \varepsilon_2\right)\sin\theta\cos\theta + \gamma_{23}(\cos^2\theta - \sin^2\theta) \\ \gamma_{nl} &= \gamma_{31}\sin\theta + \gamma_{21}\cos\theta \end{aligned} \tag{10}$$

The onset strain ε_{mat}^{0C} is obtained from the value of ε_{mat} at the onset of matrix compressive failure. The expression for final failure strain ε_{mat}^{fC} is:

$$\varepsilon_{mat}^{fC} = \frac{2G_{matC}^C}{\sigma_{mat}^{0C} L^c} \tag{11}$$

Where G_{matC}^{C} denotes the fracture toughness. The determination of the onset stress σ_{mat}^{0C} is similar to that of the ε_{mat}^{0C}, i.e.:

$$\sigma_{mat}^{0C} = \sigma_{mat} |_{F_m^C=1} = \sqrt{\langle \sigma_{nn} \rangle^2 + \tau_{nt}^2 + \tau_{nl}^2} |_{F_m^C=1} \tag{12}$$

2.1.3 Strain rate based progressive damage material model

Based on the above damage initiation criteria and damage evolution laws, the material behaviour of CFRPs under quasi-static loading could be characterised. However, the strain rate effect should be further considered as the cutting process is far more intensive than the general mechanical testing. In work by Daniel et al. [33], the strength variation of CFRPs with the strain rate was described using a logarithmic equation, and incorporated into the failure criteria developed by them earlier. With these new strain rate dependent failure criteria containing three failure modes, the damage initiation of composite material subjected to quasi-static or dynamic loading was defined.

In this paper, a similar approach is adopted to develop the strain rate based progressive damage model. Specifically, the material properties (i.e., strength, fracture toughness) are expressed as functions of the corresponding strain rates, the reference strain rate and the properties at the reference strain rate first. The changes in strength and fracture toughness are then implemented into the failure criteria of Subsection 2.1.1 and the damage evolution laws of Subsection 2.1.2, respectively. In this manner, the damage initiation and propagation under different strain rates could be predicted after acquiring the strength and fracture toughness at the reference strain rate. Notably, since the carbon fibre is a strain rate insensitive material [55], while the properties of matrix increase significantly with the increase of strain rate [56-59], only the variations in matrix dominated strength and fracture toughness are considered in this investigation.

When establishing the relationship between material property and strain rate, the most difficult process is the collection of the material property values at various strain rates by conducting tremendous amounts of tests. For the T800S/3900-2B CFRPs, although their material properties under reference strain rate have been obtained, there are few studies on the dynamic characteristics. To this issue, dynamic behaviour of CFRPs with similar mechanical performance is referred to determine the material property functions. More specifically, the strength and fracture toughness values (dots in Fig. 3) under various strain rates were collected from previous studies [33-35, 45, 58, 60-65] to be the original data firstly. Then, Eq. 13 which has been frequently utilized in the existing works [33, 40, 58, 60] was chosen to represent the strength change with strain rate. At the meantime, three functions shown in Eq. 14 were referred to fit the fracture toughness to strain rate curve [44, 45, 58]. Subsequently, the material constants (C_S, C_{G_C} and N_{G_C}) of the fitting functions were calculated with a developed MATLAB program and the original data, as listed in Table 2. The acquired strength to strain rate curve is illustrated in Fig. 3a, and it could be proved by the Adjusted R^2 in Table 2 that the goodness of fit is acceptable. In addition, the fitted curves for the fracture toughness are shown in Fig. 3b, and the function ② of Eq. 14 was selected to describe the fracture toughness variation with strain rate after comparing the three curves and analysing the Adjusted R^2 in Table 2.

$$S(\dot{\varepsilon}) = S(\dot{\varepsilon}_0)(1 + C_S \log_{10} \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}) \tag{13}$$

$$\begin{cases} ① \rightarrow G_C(\dot{\varepsilon}) = G_C(\dot{\varepsilon}_0)(1 + C_{G_C} \log_{10} \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}) \\ ② \rightarrow G_C(\dot{\varepsilon}) = G_C(\dot{\varepsilon}_0)(1 + C_{G_C} (\dot{\varepsilon})^{N_{G_C}}) \\ ③ \rightarrow G_C(\dot{\varepsilon}) = G_C(\dot{\varepsilon}_0) C_{G_C} (\dot{\varepsilon})^{N_{G_C}} \end{cases} \tag{14}$$

In Eqs. 13 and 14, $\dot{\varepsilon}$ is the strain rate and $\dot{\varepsilon}_0$ denotes the reference strain rate ($\dot{\varepsilon}_0 = 10^{-4}\,\mathrm{s}^{-1}$). $S(\dot{\varepsilon}_0)$ (S = strength (Y^T, Y^C, S_{12}, S_{13}, S_{23})) and $G_C(\dot{\varepsilon}_0)$ (G_C = fracture toughness (G_{2C}^T, G_{matC}^C)) represent the strength and fracture toughness under reference strain rate, respectively.

With Eqs. 13 and 14, the strain rate based progressive damage model could be defined by recasting Table 1 and Eqs. 3, 4, 6-9 and 11. The damage initiation criteria incorporating the strain rate effect are shown in Table 3. Where $S_{23}^A(\dot{\varepsilon})$ and $\mu_{nl}(\dot{\varepsilon})$ are expressed as:

$$S_{23}^A(\dot{\varepsilon}) = \frac{Y^C(\dot{\varepsilon}_2)}{2\tan(\theta)}, \quad \mu_{nl}(\dot{\varepsilon}) = S_{12}(\dot{\varepsilon}_{12}) \frac{\mu_{nt}}{S_{23}^A(\dot{\varepsilon})} \tag{15}$$

At the same time, the dynamic damage evolution laws could be described with the damage factors as follows:

$$\begin{gathered} d_f^T = \frac{\varepsilon_1^{fT}(\varepsilon_1 - \varepsilon_1^{0T})}{\varepsilon_1(\varepsilon_1^{fT} - \varepsilon_1^{0T})}, \quad d_f^C = \frac{\varepsilon_1^{fC}(\varepsilon_1 - \varepsilon_1^{0C})}{\varepsilon_1(\varepsilon_1^{fC} - \varepsilon_1^{0C})} \\ d_m^T(\dot{\varepsilon}) = \frac{\varepsilon_2^{fT}(\dot{\varepsilon})(\varepsilon_2 - \varepsilon_2^{0T}(\dot{\varepsilon}))}{\varepsilon_2(\varepsilon_2^{fT}(\dot{\varepsilon}) - \varepsilon_2^{0T}(\dot{\varepsilon}))}, \quad d_m^C(\dot{\varepsilon}) = \frac{\varepsilon_{mat}^{fC}(\dot{\varepsilon})(\varepsilon_{mat} - \varepsilon_{mat}^{0C})}{\varepsilon_{mat}(\varepsilon_{mat}^{fC}(\dot{\varepsilon}) - \varepsilon_{mat}^{0C})} \end{gathered} \tag{16}$$

Where the dynamic matrix dominated damage onset strains and final failure strains are:

$$\varepsilon_2^{0T}(\dot{\varepsilon}) = \frac{Y^T(\dot{\varepsilon}_2)}{E_2}, \quad \varepsilon_2^{fT}(\dot{\varepsilon}) = \frac{2G_{2C}^T(\dot{\varepsilon}_2)}{Y^T(\dot{\varepsilon}_2)L^c}, \quad \varepsilon_{mat}^{fC}(\dot{\varepsilon}) = \frac{2G_{matC}^C(\dot{\varepsilon}_2)}{\sigma_{mat}^{0C} L^c} \tag{17}$$

This novel damage model is implemented into Abaqus/Explicit by a user-defined subroutine (VUMAT) to simulate the CFRP cutting processes in different cutting conditions applied. A state variable (SDV34) is defined in the VUMAT to control the element deletion due to the stiffness degradation and final failure of the material. Since a small localised material stiffness could cause an excessive element distortion and thus result in the aborting of calculation, the SDV34 is activated once the damage factor d reaches 0.99, which helps to maintain some residual stiffness when the element is deleted. In addition, the material properties of the T800S/3900-2B CFRPs at the reference strain rate are obtained by consulting manufacturers and referring to Reference [17, 23], as shown in Table 4.

2.2 FE model details

The geometries of the tool and workpiece, mesh distribution, boundary conditions and interaction play important roles in the simulation of CFRP cutting. Therefore, these points are clarified in this section.

2.2.1 Geometric model and element setting

The geometric model for the simulation of CFRP orthogonal cutting is shown in Fig. 4. In order to improve the computational efficiency, the workpiece is set to be a deformable solid with a length of 1.2 mm, a height of 1 mm and a width of 0.1 mm (z direction in Fig. 4b), which are smaller than those applied in experiments. To further reduce the computing time with a guaranteed accuracy, the mesh density in the focused cutting area of the workpiece is refined while the relevant coarse element size is defined in the rest area. 8-node linear brick elements with reduced integration (C3D8R) are adopted for the workpiece, and the enhanced hourglass control approach is applied to minimise the potential risk from the hourglassing issue. Since this work does not consider the influence of tool deformation and wear on the cutting process, the tool is defined as an analytical rigid shell for a higher computation efficiency. The clearance angle of the tool is set to be 5º. Moreover, the rake angles of the cutting tool are defined as 5º, 15º, 25º, 35º and 45º, respectively, to investigate the dependency of the composite damage severity onto the tool rake angle during cutting. The tool geometric parameters are listed in Table 5.

2.2.2 Boundary conditions and interactions

In this model, the cutting motion is conducted by moving the tool while fixing the workpiece. The movement of the tool is allowed only along the X axis in Fig. 4. Constant cutting speeds are applied to the cutting tool at 10 mm/s, 100 mm/s, 1000 mm/s, and 5000 mm/s to assess the damage of the workpiece. The CFRP component is clamped by limiting all degrees of freedom of the nodes at the bottom of the workpiece. As shown in Fig. 4, the fibre orientation φ is defined based on the coordinate system of the FE model in this research. Considering that the material removal mechanisms may vary with the fibre cutting angle, the cutting processes of unidirectional CFRPs with the typical fibre orientations of 0°, 45°, 90°, and 135° are parametrically studied. In addition, the subsurface damages induced under 50 μm, 100 μm, 150 μm, and 200 μm cutting depths are predicted by the proposed model. The processing conditions are summarised in Table 5.

During the CFRP cutting, the complicated dynamic interactions need to be modelled between the tool and workpiece. The normal and tangential behaviours along the contact surface are defined while the hard contact is utilized to characterise the normal behaviour and the tangential behaviour is simulated based on the Coulomb friction algorithm. It should be noted that the tool-workpiece friction coefficient varies with the fibre cutting angle. Therefore, the friction coefficients of 0.3, 0.6, 0.8 and 0.6 are individually applied in the cutting modelling of the unidirectional CFRPs with 0°, 45°, 90° and 135° fibre orientations, respectively [29].

3 Experimental setup

The orthogonal cutting experiments are designed and performed in this work to validate the developed damage model and its accuracy to predict the CFRP cutting on the macro scale. The experimental setup is illustrated in Fig. 5. During these experiments, the CFRP cutting process is planned to be recorded. In order to capture clear video, the camera should be steadily fixed. Due to that the lens needs to be focused on the tool tip throughout the whole cutting process to shoot the complete chip formation procedure. The cutting tool is fastened on the platform to keep it still. The workpiece is constrained on the platform powered by the linear motor, allowing it to move in a straight line at a constant speed under the traction of the linear motor. The composite cutting is then performed by a stationary tool with the CFRP part feed-in only. For the recording of the cutting process, a PHOTRON SA5 high-speed camera with a VH-Z50L microscopic lens is selected. Additionally, a KISTLER 9257B three-component dynamometer is clamped under the cutting tool to measure the cutting force. A 5080 amplifier, a 5697A data acquisition and a force record terminal are combined to transmit and collect the force signals. The original signals of cutting forces are acquired at a sampling frequency of 12 kHz, and they are visualised and analysed with the commercial software DynoWare.

The unidirectional CFRP laminates used in the experiments are made from T800S/3900-2B prepregs, which are 4 mm in thickness with 20 layers. These laminates are cut into small sheets with the dimension of 50 mm × 90 mm, to facilitate the clamping requirement. The unidirectional CFRP workpieces with four typical fibre orientations, i.e. 0°, 45°, 90° and 135°, are prepared to experimentally observe the composite machining under various fibre cutting angles. The cutting tool is made from the cemented carbide. The clearance angle is equal to that in the FE model, and a representative rake angle of 25° which is frequently utilised in the CFRP cutting is applied. It is worth noting that a new tool is employed for each cutting test to avoid any inaccurate differences in experiments introduced by the tool wear. Microchipping of the cutting edge due to a large cutting depth could also decrease the reliability of the results, hence the 50 μm cutting depth is determined in these verification experiments. It is found by testing the parameters of the high-speed camera that only fuzzy and dim video could be captured under high cutting speed, the CFRP cutting is thus conducted with a speed of 10 mm/s for validating the numerical modelling by the same condition. In addition, the experiments with the same processing conditions are repeated three times to reduce the error.

4 Simulation validations and result discussions

In this research, the processing conditions of the numerical model are determined to be consistent with those in the experiments where the orthogonal cutting of CFRPs with four typical fibre orientations are simulated. The cutting process, chip formation, and cutting force are numerically predicted by the FE model with and without the strain rate effect considered. These numerical results are compared with the experimental measurements to verify the strain rate based progressive damage model and the FE model. Afterwards, with the aim of optimising the tool geometry and processing parameters, the effects of the cutting speed, tool rake angle and cutting depth on the subsurface damage are assessed using the validated simulation model.

4.1 The cutting process and chip formation

The cutting processes of CFRPs by the developed failure model with and without strain rate effect are shown in Figs. 6-9, including the experimental photos recorded as validation. In the simulation outputs, the Mises stress distribution is presented to assist the analysis of the material removal. When cutting CFRPs at a fibre cutting angle of 0°, similar chip formation processes are modelled by the numerical models that use the strain rate dependent and independent material models, respectively, as shown in

Fig. 6a-f. The stress of the elements near the tool tip increases under the squeezing of the tool and a crack is then initiated and propagated along the longitudinal direction while the material above the tool tip is lifted. With the further advances of the tool, the lifted part is bent and fractures, and forms sheet-like chips. This simulated material removal process is consistent with the experimental observations, as shown in Fig. 6g-i. In this process, the fracture form of the CFRPs is mainly bending.

However, the difference between the simulation results of the two models is also obvious. The damage model without the strain rate performed has predicted a long crack generated in the workpiece, meanwhile, the material above the tool tip has not been in-situ fractured (see Fig. 6f) comparing to the experimentally captured record. The cutting progression by the model that incorporates the strain rate effect has better agreed with the experimental observations. The crack only propagates a short distance and the chips have been then progressively developed with the cutting process (see Fig. 6c and 6i). Such differences in the simulation results of the two models can be explained as follows. In this machining process, although the cutting speed is low, the strain rate of the material is greater than the reference strain rate. With the increase of strain rate, the matrix dominated strength and fracture toughness rise (see Fig. 3). Therefore, for the FE model that does not adopt the strain rate based material model, material properties in the transverse direction are smaller than those of the practical experiment. Under this circumstance, the simulated crack is easy to expand along the longitudinal direction. In addition, the low material performance weakens the constraint on the material above the processing surface, which leads to difficulties in the bending and removal of this material. By contrary, when the influence of strain rate on the material properties is involved, the matrix dominated strength and fracture toughness are improved, and are closer to those in the experiment. Thus, the predicted workpiece cracking and chip formation processes are consistent with the experimental results.

For the cutting of 45° fibre orientation CFRPs, both simulation outputs (see Fig. 7a-f) by two FE models (with and without strain rate effect applied) show that in the early stage, due to the continuous push of the tool, the stress increase occurs on the workpiece at the position that contacts the tool tip and in the longitudinal direction of CFRPs. The material near the tool tip is greatly deformed, and the elements are crushed. As the tool further feeds in, the CFRPs above the tool tip slide upward along the longitudinal direction, and cracks are induced in Area S (see Fig. 7b, 7e, and 7h). Subsequently, chips are formed. The predicted cutting processes agree well with the experimental results that shown in Fig. 7g-i.

By comparing the simulation results modelled with and without the strain rate effect, it is found that, in the latter one, the cracks induced in Area S gradually extend up to the free surface of the workpiece. At the same time, the material being cut slips upward along the fracture plane in Fig. 7f, and it is removed eventually and forms the block-shaped chips. While for the results of the strain rate dependent model, the induced cracks could not reach the workpiece surface. The material above the tool tip curls under the action of the tool rake face, and strip-shaped chips are generated, which is more consistent with the experimental observations, as shown in Fig. 7c and 7i. The reason for this phenomenon is that the matrix dominated strength and fracture toughness are increased after combining the strain rate effect. The higher material properties allow greater deformation of the material in Area S before that the cracks propagate to the free surface of the workpiece. Therefore, the material is hard to be removed and continuous chips are resulted.

Figure 8a-f presents the cutting processes of the 90° fibre orientation CFRPs predicted by two numerical models. It indicates from Fig. 8a and 8d that, the material in front of the tool cutting edge is bent under the push of the tool and thus the stress increases. With the progressive feeding of the tool, the bending deformation of the material gradually enlarges, and the workpiece fractures since the bending stress exceeds the ultimate strength. In the meantime, the elements above the tool tip are removed due to the squeezing of the tool rake face. The simulation results and the experimental recording (see Fig. 8g-i) are in good agreement.

It is also clear that there are differences existed between the outcomes of the two models. In the results that without considering the strain rate effect, the elements that contact the tool tip are removed first rather than other elements. Then, the elements on the processing plane fail progressively with the feed of the tool. The material above the processing plane fractures and forms chips. Whereas, from the outputs of the strain rate based model, it is obvious that the maximum bending deformation of the material is greater than that displayed in the results of the strain rate independent model. In addition, the material (in Area B) in front of the elements (in Area A) being cut fractures first and forms cracks (see Fig. 8b). The cracks extend upward to the workpiece surface subsequently, and the elements on the cutting plane that contact the tool tip fail and are deleted, as shown in Fig. 8c. At this time, powder-like chips are generated. The whole process is closer to the experimental results than that simulated by the former one. These differences could be explained by analysing the influence of the strain rate. Before the strain rate effect is involved, the matrix dominated performance of the material is not enhanced, and a small bending deformation would lead to the removal of the elements. By contrary, in the strain rate based model, increased strength and fracture toughness are applied in the transverse direction, and thus a great bending deformation is required for the fracture of the material. Furthermore, since the deformation of the elements in Area B is larger than that in Area A, the elements in Area B fracture first.

When CFRPs are cut under 135° fibre cutting angle, the simulation results could be described as follows. As seen in Fig. 9a and 9d, the material that contacts the tool rake face deforms. On the workpiece at the position near the tool tip and in the longitudinal direction of CFRPs, the stress increases. A crack is induced in the workpiece and it propagates downward along the longitudinal direction, which results in damage beneath the processing surface. In addition, the material in the cutting area is bent and fractures under the continuous lifting and squeezing of the tool rake face, and chips are formed. The simulation results agree well with the experimental observations.

However, the predicted damage propagations are different by two models implemented. When the strain rate effect is not involved, the matrix dominated material properties are relatively low. In this case, the cutting produced crack is easy to extend downward and it can cause the splitting of the entire workpiece, which does not match the experimental results to some extent. After adopting the strain rate dependent material model, the material performance is closer to that in the experiments, and the simulation outputs are consistent with the experimental results.

Through comparison of material removal and chip formation processes for the various fibre orientations, the strain rate based model has demonstrated a great potential to improve the modelling accuracy on the failure development with reference to the experimental evidences. In addition, based on the above analyses, it could be concluded that the cutting process of CFRPs is actually significantly dependent on the fibre cutting angle. The variation in fibre cutting angle will lead to the change in the distributions of material deformation and stress, and cause diverse crack propagation directions and material fracture positions. Eventually, all these changes result in different material removal and chip formation mechanisms.

4.2 The cutting force

Figure 10 illustrates the simulation and experimental cutting force per unit width for the unidirectional CFRPs under four typical fibre cutting angles. The force values are obtained by calculating the average cutting force in the machining processes. It could be seen the numerical predicted cutting force values per unit width by either model with and without the strain rate effect applied have shown a consistent trend with that of the experimental results. As the fibre orientation increased, the cutting force rises first and then decreases. The maximum cutting force is about 45 N/mm, and it is reached when the fibre orientation is 90°. This conclusion agrees well with our previous research [26], and it could be explained as follows. In the cutting of CFRPs with 0° fibre orientation, a crack is induced and propagated along the longitudinal direction, and the material being cut is lifted and bent. Therefore, compared with the CFRP cutting under 45°, 90° and 135° fibre cutting angles, the workpiece imposes the weakest resistance on the tool in the cutting direction in this case. The smallest cutting force is hence resulted at the 0° fibre orientation. With regard to the cutting of CFRPs consisting of 45° fibres, although the workpiece cracks in this process too, the crack growth direction is not parallel to the cutting direction. The tool tip has to continuously crush the material on the cutting plane during the cutting, thus the cutting force is greater than that at the 0° fibre orientation. Furthermore, when cutting CFRPs under 45° fibre cutting angle, the failure mode is mainly crushing and the material being cut is easy to slide upward along the longitudinal direction. This material removal process is different from the chip formation of CFRPs with 90° fibre orientation in which the material is fractured due to bending and the chips are generated under the squeezing of the tool rake face. These differences lead to the fact that the cutting force at 90° fibre orientation is higher than that at 45° fibre orientation. During the cutting process of CFRPs with 135° fibre orientation, the material at the right side of the crack (see Fig. 9b and 9e) and below the cutting plane is not able to constrain the material being cut. Under this circumstance, the resistance of the workpiece on the tool is weaker than that at the 90° fibre orientation, and thus lower cutting forces are obtained under 135° fibre orientation. Additionally, for the CFRPs with 135° fibres, the material in the cutting area fractures under the continuous pushing of the tool rake face, while the material being cut is easy to slide upward to form the chips in the cutting of CFRPs with 45° fibre orientation. Therefore, the cutting force at 135° fibre orientation is higher than that at 45° fibre orientation.

In addition, Fig. 10 indicates that results with more accuracy are acquired after incorporating the strain rate effect, and the average error between the simulation and experimental outputs decreases from about 25% to 11.5%. The simulation errors of the FE models with and without strain rate effect when modelling the cutting of CFRPs with the four fibre orientations are listed in Table 6. The reason for the improvement of the force prediction accuracy could be similarly explained by discussing the effect of strain rate on the cutting process of CFRPs with the four fibre orientations (see Subsection 4.1 with Figs. 6-9). For the CFRP cutting at 0° and 45° fibre cutting angles, on the basis of Subsection 4.1, the cracking along the longitudinal direction plays an important role in the material removal. Therefore, when the strain rate effect is considered, the matrix dominated strength is improved and the crack is hard to initiate and extend. Under this circumstance, the cutting forces increase, and are closer to the experimental results. For the cutting of 90° fibre orientation CFRPs, the material in front of the tool cutting edge is bent and the workpiece fractures once the bending stress exceeds the ultimate strength. After adopting strain rate dependent material properties, higher strengths are applied in the transverse direction. Hence, larger bending deformations are required for the material removal, and thus the predicted cutting force is higher and the error is reduced. When cutting CFRPs with 135° fibre orientation, the crack propagates downward along the longitudinal direction. Subsequently, the material above the tool cutting edge fractures and is removed under the continuous lifting and squeezing of the tool rake face. In this process, the deeper the crack extends, the more material is cut and the higher the cutting force is. The application of the strain rate based material model improves the material properties and suppresses the cracking of the workpiece, therefore, the material being cut is reduced and a lower cutting force is modelled. To further verify this conclusion, the histories of cutting force per unit width for the CFRPs with 135° fibre orientation are analysed. The force curves recorded experimentally and numerically within the stable stage (0.02 s - 0.035 s) of the cutting process are illustrated by Fig. 11. It can be seen that after considering the strain rate effect, the predicted cutting force is closer to the experimental value whereas the FE model without strain rate effect applied has over-estimated the cutting force.

4.3 Subsurface damage analyses for the cutting of 135° fibre orientation CFRPs

According to the analysis in Subsection 4.1, the cutting process for the CFRPs with 135° fibre orientation is selected as the typical example for parametric studies to improve the processing quality, which is mainly attributed to the deeper cracks and more internal damages are found by previous analyses and discussions. The influences of the cutting speed, tool rake angle and cutting depth on the subsurface damage depth are evaluated using the strain rate based model. The subsurface damage is assessed by the damage factor d for the matrix tensile failure mode that is previously introduced. Since the potential damage could reduce the bearing capacity of the workpiece, the area where the damage has been initiated ($d > 0$) and not just the elements completely fail ($d > 0.99$) is determined to be the subsurface damage zone, as shown in the following simulation results. The value of the damage factor d is collected by a predefined state variable (SDV15) in the VUMAT.

4.3.1 Influence of cutting speed

Four cutting speed values of 10 mm/s, 100 mm/s, 1000 mm/s and 5000 mm/s are numerically predicted by the strain rate based model to model their subsurface damage distributions in the cutting processes of CFRPs with a 25° rake angle tool under 50 μm cutting depth, as shown in Fig. 12. Figure 13 illustrates the variations in the cutting force per unit width and subsurface damage depth with the various cutting speeds. It can be concluded that the subsurface damage and cutting force are remarkably decreased with the increase of the cutting speed until 100 mm/s. After that, for the increased cutting speeds, the subsurface damage and cutting force are almost constant. As seen in Fig. 3a, the matrix dominated strength of CFRPs is directly proportional to the logarithm of strain rate, which means that the growth rate of the strength reduces with the rise of strain rate. Therefore, when the cutting speed is low, the strength increases sharply with the enhancements of the cutting speed and strain rate. In this case, the downward extension of the crack occurred in the cutting of 135° fibre orientation CFRPs becomes harder, and the subsurface damage depth decreases. At the same time, less material is involved in the removal process and the cutting force is lower. When it comes to high cutting speeds, the improvement of the strength is not obvious, thus small changes have taken place in the subsurface damage and cutting force.

4.3.2 Influence of rake angle

Similarly, the tool rake angles of 5°, 15°, 25°, 35° and 45° are numerically studied for the cutting process under cutting depth of 50 μm, as shown in Fig. 14. Based on the results of Subsection 4.3.1, the predictions were conducted at 100 mm/s cutting speed. The simulation results indicate that, within the range of the assessed tool rake angles, the material above the processing surface fractures under the squeezing of the tool rake face. This chip formation process agrees well with the analyses in Subsection 4.1. The propagation of the crack is dependent on the material properties and the action of the tool tip on the workpiece. Therefore, the tool rake angle has little effect on the crack length, and the subsurface damage depth changes slightly with the increase of tool rake angle, as shown in Fig. 15. In addition, due to that the material being cut is bent and the tool-workpiece contact surface is parallel to the tool rake face (see Fig. 14), the action force on the workpiece is perpendicular to the tool rake face. The component of the action force in the cutting speed direction is smaller for a larger rake angle. Therefore, the cutting force reduces with the rise of tool rake angle, as illustrated in Fig. 15.

4.3.3 Influence of cutting depth

Figure 16 shows the simulated subsurface damage distributions when machining CFRPs with a 25° rake angle tool under 50 μm, 100 μm, 150 μm and 200 μm cutting depth and 100 mm/s cutting speed. It is seen from Fig. 16 that with the rise of cutting depth, more material is bent under the push of the tool rake face. The resistance of the workpiece on the tool is enhanced, and the tool does more work to remove the material. Therefore, a larger cutting force per unit width is produced at a higher cutting depth, as shown in Fig. 17. Moreover, the resistance of the workpiece is generated by the deformation of the material being cut. In other words, the deformation of the workpiece in front of the tool tip is increased under a greater cutting depth, and the cracking depth is enlarged at the same time (see Fig. 16). Therefore, larger subsurface damage depths are induced with the increase of cutting depth.

5 Conclusions

In this paper, a macro numerical model for the CFRP orthogonal cutting is established based on a novel material failure model to investigate the material removal and chip formation mechanisms and the damage response. The material model is developed by incorporating the strain rate effect across the damage initiation (combined Hashin and Puck criteria) and evolution laws. With this numerical model, the machining processes and cutting forces of the unidirectional CFRPs under four typical fibre cutting angles are predicted. These results agree well with the experimental observations. Then, parametric studies are conducted to find out the influences of the cutting speed, tool rake angle and cutting depth on the subsurface damage in the machining of 135° fibre orientation CFRPs. The main conclusions are as follows:

(1) By comparing with the simulation results of the strain rate independent model, the cutting processes and forces predicted by the strain rate based model are closer to the experimental outputs, and the average prediction error of the cutting forces decreases of about 15%. This is because the changes in material properties due to the variation in strain rate are involved in the latter model, and the matrix dominated strength and fracture toughness are more consistent with those in the experiment. Therefore, the strain rate based model is more suitable for the research of CFRP machining.

(2) The material removal and chip formation mechanisms are significantly dependent on the fibre orientation, and the strain rate based model could precisely describe the cutting processes, especially the damage initiation and propagation. In the cutting of CFRPs at 0° fibre cutting angle, the CFRPs above the tool tip are bent and fracture, which form sheet-like chips. When cutting 45° fibre orientation CFRPs, the material being cut slips upward along the longitudinal direction and curls, and strip-shaped chips are generated eventually. For the 90° fibre orientation CFRPs, the material in front of the elements being cut fractures and forms cracks, then the cracks extend upward to the workpiece surface and powder-like chips are produced. When the workpiece is cut under 135° fibre cutting angle, a crack is induced and propagates downward along the longitudinal direction, and the material in the cutting area is bent and fractures and forms chips eventually.

(3) With the increase of fibre orientation, the cutting force rises first and then decreases, and it reaches the maximum value at 90° fibre orientation. In addition, after considering the strain rate effect, the predicted cutting forces are higher except for the 135° fibre orientation.

(4) The subsurface damage in machining 135° fibre orientation CFRPs decreases with the rise of cutting speed until 100 mm/s, while it keeps almost constant for higher cutting speeds. The subsurface damage variation is independent to the tool rake angle. Moreover, a larger cutting depth could result in an increased subsurface damage depth.

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