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Elliptic vibration-assisted cutting of fibre-reinforced polymer composites: Understanding the material removal mechanisms

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ABSTRACT

This paper develops an elliptic vibration-assisted (EVA) technique to effectively cut fibre-reinforced polymer (FRP) composites using a simple tool. A novel vibrator was invented to work at the anti-resonant frequency to realize stable and high variational velocities. A three-dimensional microstructure-based finite element model was also established to explore the material removal mechanisms in the EVA cutting. It was found that the application of vibration can significantly decrease the cutting forces and reduce the subsurface damage in a workpiece. The vibration in the cutting direction is more effective in reducing the cutting force, but that normal to the cutting direction has the advantage of chip removal. When the vibration is applied to both the directions in the EVA cutting, an optimal cutting process can be reached, providing much smaller cutting forces, a much improved surface integrity, and an extended tool life. The study concluded that the ratio of the tool-feed-rate to the maximum vibration velocity in the cutting direction, and the ratio of the cutting distance in a single tool vibration cycle to the fibre diameter are the key parameters. To maximise the advantage of the EVA cutting, it is necessary that these two parameters are below their critical values.

1. Introduction

Fibre-reinforced polymer (FRP) composites have been widely used in industry due to their high strength and stiffness to weight ratio. However, machining of FRP composite products is quite difficult, because of the significant difference in mechanical properties of fibres and matrix. As a result, a machined FRPs usually contains various damages, such as fibre pull-out, fibre fracture, matrix cracking, fibre–matrix debonding and delamination [1–4]. To date, most experimental investigations on the machining of FRP composites are on the following issues: effect of fibre or matrix types [5,6], influence of fibre volume fraction and orientations [2,7], role of tool materials and geometries [8–10], contribution of the depth of cut [11], and selection of processing parameters [12–14]. However, these studies are limited to traditional machining methods, such as turning, milling, drilling and grinding, and are still facing the poor surface integrity problems highlighted above. In order to reveal the machining mechanisms, corresponding theoretical analysis has also been carried out, using various modelling methods [3,4,15–19]. The finite element (FE) analysis has also been conducted, of which some were based on the consideration of equivalent homogenous materials [20–23] and some others involved the microstructures of FRP composites [24–26]. Nevertheless, these are still insufficient to reflect the real complex structure of FRPs, especially in the understanding of the dynamic material removal process in machining.

On the other hand, it has been a common understanding that grinding is more appropriate for machining FRP composites [27–29], because in grinding the depth of cut of individual cutting edges is usually smaller than the diameter of a fibre [2]. However, in many cases, grinding is often inefficient. This raises an important question: Can a FRP composite be cut at a nominally large depth of cut but with a small tool–composite interaction to improve the surface integrity while using a simple tool?

Vibration-assisted cutting may provide a satisfactory answer to the above question, because this kind of cutting methods adds a displacement of a micro-scale amplitude with an ultrasonic frequency to the tip motion of a cutting tool. The process effectiveness has been experimentally evidenced by the machining of many single phase materials such as metals and ceramics [30,31]. The advantage is that the ultrasonic vibration alters the tip trajectory of a tool, which consequently makes the instant depth of cut much smaller than a fibre diameter. This may in turn improve the surface integrity as pointed out by Zhang and Xu [2,32]. However, the immediate challenge is as follows: (1) what vibration amplitude, frequency and tool tip trajectory would be appropriate for a high performance FRP cutting? (2) how can the material removal

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mechanisms be explored such that a deep understanding can be achieved for optimising a cutting process?

The objective of this paper is to develop a vibration-assisted technique for the effective cutting of FRPs and explore the material removal mechanisms associated with the process. Both experimental and numerical methods will be employed to establish the fundamentals.

2. Principle and modelling

2.1. Principle

A fibre in an FRP composite is often made of a brittle material, such as carbon and glass. To facilitate the breakage of such fibres in cutting the composite, an elliptic tool tip motion as illustrated in Fig. 1a can be effective, because the tip motion, when properly applied, can generate a local tensile stress in the fibre. For convenience, this process is called an elliptic vibration-assisted (EVA) cutting, of which the cutting tool feeds at a nominal feed rate, v, while vibrates elliptically at an ultrasonic frequency and a micro scale amplitude in the xz-plane. The feed rate is smaller than the maximum vibration speed in x-direction, such that an intermittent cutting [33–35] is generated in each vibration cycle of the tool. In each cycle, cutting takes place only when the tip wedges into the workpiece, and hence a chip is mainly pulled up when the tool moves upward in the chip flow direction. To facilitate the breakage of the fibres and matrix, the cutting distance within a cycle of the tool vibration, Δ, is set to be smaller than the fibre diameter, D.

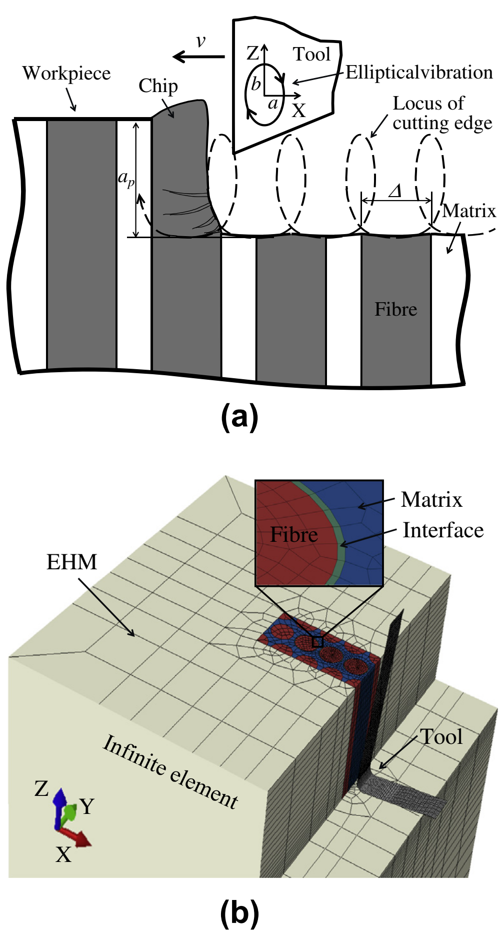

Fig. 1. Illustration of (a) EVA cutting of FRP composite and (b) its FE micro-scale model.

Consequently, the surface quality can be improved as concluded by Wang and Zhang [2] from a qualitative mechanics analysis.

2.2. Micro-scale modelling

To understand the material removal mechanisms in an EVA cutting, a 3D microstructure-based FE model (Fig. 1b) was established by ABAQUS. The model was constructed with three layers: a microstructured layer, an equivalently homogeneous material (EHM) layer and an infinite elements layer. The microstructured layer was in the middle of the model, whose thickness was set to be the same as that of the cutting tool as shown in the figure. This layer consisted of three phases of unique material properties, i.e., the fibre, the matrix and the fibre–matrix interface, and was meshed by 8-noded brick elements. For the sake of computational efficiency but without losing the generality, the material layers that sandwiched the microstructured layer were treated as an EHM. To avoid the boundary effect, infinite elements (CIN3D8) were arranged around the control volume, except its front and top surfaces. The material properties of the infinite elements were set to be the same as the EHM. The cutting tool was regarded as a rigid body and its motion was supposed as follows:

$$x_{Tool}(t) = a\cos(2\pi ft) \qquad z_{Tool}(t) = b\cos(2\pi ft + \psi) \tag{1}$$

where a and b are the vibration amplitudes in x- and z-directions, respectively; f is the vibration frequency; and ψ is the phase difference. The relative instantaneous cutting speed of the tool to the workpiece is therefore

$$v_x(t) = -2\pi fa\sin(2\pi ft) + v \qquad v_z(t) = -2\pi fb\sin(2\pi ft + \psi). \tag{2}$$

Based on the relative motion of the tool vibration to the feed direction, there can be three types of vibration-assisted cutting: (1) cutting-directional vibration-assisted (CDVA) cutting where the tool vibrates in the cutting direction only (i.e., $a \neq 0$ but $b = 0$), (2) normal-directional vibration-assisted (NDVA) cutting (i.e., $a = 0$ but $b \neq 0$), and (3) EVA cutting (i.e., $a \neq 0$ and $b \neq 0$).

3. The ultrasonic vibrator

3.1. The EVA cutting system

Fig. 2 shows a schematic illustration of the EVA cutting system, consisting of a vibrator to generate an elliptic high frequency vibration, a cutting tool, a support system and a power supply system. The vibrator was designed by bonding four axis-symmetric distributed piezoelectric (PZT) actuators, denoted by A, B, C and D, on a cylindrical body made of stainless steel SUS304. In order to realize the ultrasonic vibrations in both cutting and vertical directions,

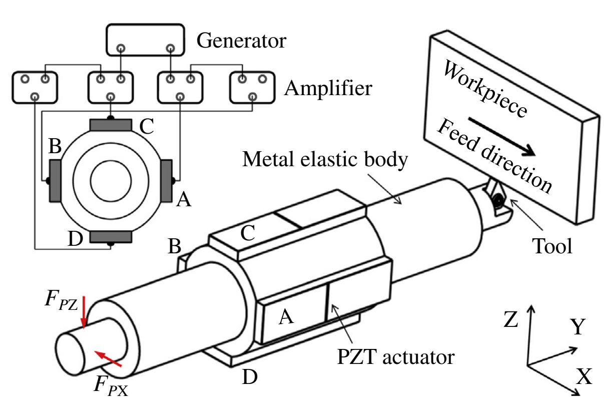

Fig. 2. Illustration of EVA cutting system.