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Numerical modeling and FE analysis of CFRP/Ti stack orthogonal cutting

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Abstract

Compared to the great interest of experimental studies on hybrid CFRP/Ti drilling, this paper provided a new contribution to study the hybrid composite machinability via the numerical approach. To this aim, the complex drilling operation was abstracted into the orthogonal cutting configuration (OCC) by considering the involved cutting sequence from one phase machining to another phase machining. The numerical model was established by incorporating four fundamental physical constituents (*i.e.*, Ti layer, interface, CFRP layer and tool part) to simulate the hybrid cutting operation. Different constitutive laws and damage criteria were implemented to construct the anisotropic machinability of the stacked composite. The induced cutting responses including specific cutting energy (u) and induced damage formation, were precisely addressed *versus* the input variables. The numerical studies highlighted that the anisotropic machinability of the CFRP/Ti stack could be reflected in a “pigeon” like u polar map *versus* fiber orientation (θ). For minimizing the severe induced damage extent, high cutting speed, as well as low feed rate, should be adopted when machining this multi-phase material.

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1. Introduction

Nowadays, the hybrid composite stack has been extensively used in modern aerospace and aviation industries for manufacturing the key load-bearing components due to its enhanced mechanical properties and improved structural functions [1]. Material made of multi-phase of carbon fiber reinforced polymer (CFRP) and titanium alloy (Ti) is a typical example of hybrid composite configuration. The key advantages of delivering energy saving and improving system performance have awarded the material a promising alternative to substituting standard composite application and single metal alloy application in various industrial sectors [2-5].

Despite its superior behavior, mechanical drilling of this hybrid composite stack still represents the most challenging task in modern manufacturing industries due to the disparate natures of each stacked constituent involved and their respectively poor machinability. For instance, the CFRP laminate shows anisotropic behavior, abrasive nature and low thermal conductivity, which leads to poor heat dissipation and excessive tool wear in cutting. For Ti alloy, the metal exhibits low thermal conductivity and strong chemical affinity to most used tool materials, which usually results in high force/heat generation, and serious tool wear predominating the machining process. Moreover, the hybrid composite machining also involves severe mechanical/physical responses transfer due to the changeable chip-separation modes ruled in the material removal process when the tool edges cutting from one phase to another phase and *vice versa*. As a consequence, the cutting conditions governing the hybrid CFRP/Ti machining are extremely harsh. Severe subsurface damage, poor machined quality, and rapid tool wear are the key cutting characteristics of the hybrid CFRP/Ti machining.

To reveal the complicated cutting physics governing the hybrid CFRP/Ti machining, tremendous experimental studies have been performed by covering various cutting aspects including machinability evaluation, subsurface damage analysis and wear mechanism inspection [1]. Despite the fact that the referred work has led to a better understanding of the cutting physics dominating the hybrid CFRP/Ti drilling, however, these researches were carried out solely via the experimental method, which exhibits time-consuming and high cost. In contrast, the numerical approach should be a promising tool that can significantly help the mechanism investigation while cutting this bi-material system. Compared to the large amount of scientific work dealing with standard composite and single Ti alloy cutting modeling, very limited publications are reported to concern the numerical modeling and FE analysis of

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hybrid CFRP/Ti machining. The key reasons can be attributed to the problem and difficulty in establishing reliable constituents accurately describing the disparate natures of the composite-to-metal system as well as the complicated modeling of the interface behavior [6]. On this basis, this paper made an attempt to address the challenging issues involved in hybrid CFRP/Ti cutting modeling via the numerical method. To avoid the high computation cost arising from the real manufacturing modeling, the simplified orthogonal cutting configuration (OCC) was adopted. Although the OCC ignored some physical details of the real tool-work interaction, it still represented the most convenient way to replicate the fundamental mechanisms dominating the actual production. To construct the anisotropic machinability of the sandwich material, different constitutive laws and damage criteria were implemented into the commercial software Abaqus/Explicit code (Version 6.11) for the establishment of each stacked phase. The physical aspects involved in hybrid CFRP/Ti machining including specific cutting energy and induced damage extent were precisely studied through the comprehensive numerical analyses. It is the key objective to investigate the parametric effects on the anisotropic machinability of the stacked composite.

2. Physical setup of the FE model

The established FE model comprised four fundamental physical constituents, *i.e.*, the tool part, CFRP phase, interface and Ti phase, as shown schematically in Fig.1 [7]. In the configuration of Fig.1, the tool edge was assumed to travel perpendicular to the CFRP/Ti boundary, which showed some differences from the drilling operation. However, under a 2D configuration, it still represented the simplified and easy way to study the fundamental cutting responses when machining the hybrid CFRP/Ti stack. Note that the use of interface here aimed to serve as a technical control for the "CFRP-to-Ti" contact management to simulate explicitly the interface delamination phenomenon during machining. Besides, a triangular traction-separation cohesive formulation together with the Benzeggagh-Kenane (BK) damage law [8] functionally available in the Abaqus/Explicit code was used to simulate the mechanical responses of the interface layer. In addition, a very small thickness approximately 5 μm was defined for the CFRP/Ti interface in order to minimize its influences on some other machining responses, *i.e.*, CFRP/Ti force generation, chip separation process, *etc*.

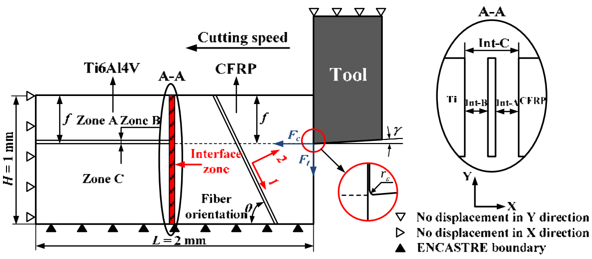

Fig. 1. Scheme of the OC model for hybrid CFRP/Ti machining (F_c denotes the cutting force and F_t signifies the thrust force) [7].

As shown in Fig.1, the tool part was assumed as a rigid body with defined geometries of rake angle, clearance angle ($\alpha = 0°$ and $\gamma = 7°$), and tool edge radius (r_ε) of 2 μm, respectively. A cutting velocity was assigned to the reference node of the tool nose in order to finalize the cutting process. For the workpiece geometries and boundary conditions (as depicted in Fig.1), sufficient cutting length of probably 1 mm were used for both CFRP phase and Ti phase in order to attain the steady cutting status. The bottom side of the FE model was restrained in all directions while the left side was constrained to move in the cutting speed direction (X direction).

The CFRP phase used here was modeled as an equivalent homogeneous material (EHM) by also considering its anisotropic behavior relative to the fiber orientation (θ). The studied CFRP laminate was a unidirectional (UD) T300/914 carbon/epoxy laminate and 4-node plane-stress CPS4R elements with reduced integration and automatic hourglass control were used to construct the CFRP-phase model. The basic mechanical/physical properties of the simulated CFRP composite were obtained from [9, 10]. Through several experimental studies, the chip separation process of CFRP laminate was confirmed to be governed by brittle fracture mechanisms following four types of failure modes, *i.e.*, fiber-tensile failure, fiber-compression failure, matrix-tensile failure and matrix-compression failure. Therefore, the commonly-used Hashin damage criteria that consider the mentioned four failure modes were adopted to simulate the rupture of the fiber/matrix system during the CFRP chip removal process. Table 1 then shows the basic expressions of the Hashin damage criteria [11, 12]. During the FE calculation, the stress at each integration point of the CFRP phase was simulated under specified time increment. Afterward, the mentioned four types of fiber/matrix failure modes were evaluated correspondingly. When any of the four failure modes reached the unity, the elastic properties of the examined elements would be degraded automatically according to their respective failure mode. Furthermore, once the elastic stiffness of the examined elements was degraded into zero, the elements would be deleted automatically from the composite phase and resulted in the complete chip separation of the CFRP material.

Table 1. General formulation of the Hashin damage criteria [11, 12].

Failure mode	Hashin failure criteria
Fiber-tensile failure ($\sigma_{11} \geq 0$)	$D_{ft}^2 = \left(\frac{\sigma_{11}}{X_T}\right)^2 + \left(\frac{\sigma_{12}}{S_L}\right)^2$
Fiber-compression failure ($\sigma_{11} < 0$)	$D_{fc}^2 = \left(\frac{\sigma_{11}}{X_C}\right)^2$
Matrix-tensile failure ($\sigma_{22} \geq 0$)	$D_{mt}^2 = \left(\frac{\sigma_{22}}{Y_T}\right)^2 + \left(\frac{\sigma_{12}}{S_L}\right)^2$
Matrix-compression failure ($\sigma_{22} < 0$)	$D_{mc}^2 = \left(\frac{\sigma_{22}}{2S_T}\right)^2 + \left[\left(\frac{Y_C}{2S_T}\right)^2 - 1\right]\frac{\sigma_{22}}{Y_C} + \left(\frac{\sigma_{12}}{S_L}\right)^2$
	Note: σ_{11} indicates the stress in the fiber direction, σ_{22} signifies the stress in the transverse direction, and σ_{12} denotes the in-plane shear stress.

The Ti phase was modeled as a fully isotropic material by using the four-node plane-strain thermally coupled quadrilateral CPE4RT elements for the whole set of the Ti elements. The basic mechanical/physical properties of the studied Ti6Al4V alloy were obtained from [13].

In addition, the most-used Johnson-Cook (JC) constitutive law and JC damage criteria were adopted to simulate the chip removal process of the Ti alloy. The basic expressions of the JC constitutive law and JC damage criteria can be found in [14]. Besides, the damage evolution was controlled by using effective plastic displacement at failure in the FE calculation. Moreover, the input JC parameters were selected from our previous work on hybrid CFRP/Ti cutting modeling [4, 7].