Finite element analysis when orthogonal cutting of hybrid composite CFRP/Ti

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Abstract. Hybrid composite, especially CFRP/Ti stack, is usually considered as an innovative structural configuration for manufacturing the key load-bearing components in modern aerospace industry. This paper originally proposed an FE model to simulate the total chip formation process dominated the hybrid cutting operation. The hybrid composite model was established based on three physical constituents, i.e., Ti constituent, interface and CFRP constituent. Different constitutive models and damage criteria were introduced to replicate the interrelated cutting behaviour of the stack material. The CFRP/Ti interface was modelled as a third phase through the concept of cohesive zone (CZ). Particular attention was made on the comparative studies of the influence of different cutting-sequence strategies on the machining responses induced in hybrid stack cutting. The numerical results emphasized the pivotal role of cutting-sequence strategy on the various machining induced responses including cutting-force generation, machined surface quality and induced interface damage.

1. Introduction
Hybrid CFRP/Ti stacks are identified as an innovative structural configuration in modern aerospace industry, which has received a wide range of applications due to their enhanced characteristics and improved structural functions favouring energy saving. The composite-to-metal alliance commonly provides superior mechanical/physical properties for the aerospace components subjected to high thermo-mechanical stresses in their service. The CFRP/Ti coupling is considered a promising candidate to override conventional single-metal or single-composite applications in the aerospace field. A typical application is the usage of wing-fuselage connections in the Boeing 787 Dreamliner.

Prior to their post applications, the hybrid CFRP/Ti stacks are usually required to be manufactured in near-to-net shape in order to achieve dimensional tolerance and assembly performance. However, machining of such hybrid composite stack is characterized as the most challenging and difficult task in modern manufacturing sectors due to the extremely poor machinability of each constituent and their disparate natures. For instance, the CFRP exhibits anisotropic and abrasive nature, which always causes serious induced damage, and excessive tool wear [1-5]. In contrast, Ti alloy has low thermal conductivity and shows strong affinity to most used tool materials, which commonly results in severe adhesion wear, high concentrated cutting temperature, etc. [6-9]. To improve the machinability of CFRP/Ti stacks, various experimental studies have been conducted in the past few decades and have led to a better comprehension of the machining phenomena induced in cutting [10-12]. However, conventional experimental methodology used in CFRP/Ti stack cutting usually shows highly cost and...
time consuming. The number of parameters to control, the exhaustive material characterisation and the
time-consuming procedure to determine various machining responses restricts its studies. In contrast,
the numerical approach should be a promising tool that capable of offering feasible investigations of
the machining results. Compared to tremendous scientific works dealing with single-metal and single-
composite cutting modelling, nearly rare literatures exist on numerical simulation of hybrid CFRP/Ti
cutting. The reason may be caused due to the complexity of various numerical parameters to control
and the difficulty encountered in the interface behaviour modelling.

The interest of improving the knowledge concerning hybrid composite cutting has motivated the
current work to develop an original FE model. In order to achieve the objective, a macro-mechanical
model was established by using Abaqus/Explicit code allowing the simulation of the complete chip
formation during the CFRP/Ti cutting process. The workpiece model consists of three constituents, i.e.,
the Ti layer, interface layer and CFRP layer, and each layer was developed individually and then
assembled to conduct the FE computation. Several aspects of the cutting phenomena activated in
different cutting-sequence strategies when cutting CFRP/Ti stacks were studied. The paper highlighted
the significant role of cutting-sequence strategy in affecting the final machining responses.

2. Numerical model for CFRP/Ti cutting

2.1. Description of OC model

For present simulations, an original FE model of hybrid CFRP/Ti stack cutting was developed in
Abaqus/Explicit code. To model 2D orthogonal cutting simulation, the quadrilateral elements with
reduced integration were considered. The proposed OC model comprises four fundamental parts, i.e.,
the tool part, CFRP part, interface part and Ti part as shown graphically in figure 1.

The total dimensions of the OC model were set as 2 mm × 1 mm (L×H) and sufficient cutting
length (around 1 mm) was made for both the Ti phase and CFRP phase in order to reach steady cutting
conditions. The cutting tool used in the FE computation was modelled as a rigid body and imposed by
a velocity to fulfil the cutting process. The tool geometries were defined by rake and clearance angles
(α = 0° and γ = 7°) and nose radius (rε = 2 μm) as depicted in figure 1. The Ti part was assumed as
fully isotropic and homogeneous material. A four-node plane-stress thermally coupled quadrilateral
element type CPS4RT which has better convergence properties was implemented for the whole set of
Ti elements. The interface part connecting Ti phase and CFRP phase was modelled by using the
cohesive element functionally available in Abaqus/Explicit code. A triangular traction-separation
cohesive formulation with linear softening is used to represent the mechanical response of the
interface layer. The CFRP part was modelled as equivalent homogeneous material (EHM) by using 4-
node plane-stress linearly interpolated elements with reduced integration and automatic hourglass
control.

The kinematic contact algorithm was assigned to the contact pairs in order to avoid element
penetration. Friction properties ruled in tool-work contact pairs were described by using Coulomb
criterion with a constant friction coefficient equal to 0.3. Fixed displacements were applied on both the bottom and left edges of the stacked model. The bottom edge of the OC model was restrained in all directions (ENCASER) while the left side was constrained to move in the X direction, as shown in figure 1.

2.2. Failure damage criteria

In FE modelling, failure damage criteria play a pivotal role in influencing the rupture phenomena of the simulated work material and determining the finally separated chip morphology during the cutting process. The disparate nurtures of each stacked constituent make it more complex/difficult to simulate the chip removal process by using single failure damage criterion. For instance, the Ti part commonly exhibits isotropic and elastic-plastic behaviour, while the CFRP part shows anisotropic performance and heterogeneity strongly varied with fibre orientation ($\theta$). The Ti phase and CFRP phase are required to implement different damage criteria to fulfil the chip separation process controlling the hybrid stack cutting. For Ti layer, the studied Ti alloy was Ti6Al4V and its properties were summarized as follows: density (4430 kg/m³), Young’s modulus (113 GPa), Poisson’s ratio (0.342), thermal expansion coefficient ($9.1 \times 10^{-6} \degree C^{-1}$), melting temperature ($T_m = 1680 \degree C$), room temperature ($T_r = 25 \degree C$), thermal conductivity (7.0 W/(m•°C)) and specific heat (546 J/(kg•°C)). The metal is assumed to suffer high plastic deformation, plane stress, strain rate and pronounced temperature effects during the cutting operation. In such case, the widely-used Johnson-Cook (JC) constitutive model and JC damage law [13, 14] were introduced to replicate the machining behaviour and cutting performance for Ti part. The expression of the JC constitutive equation is shown as follows:

$$\sigma = (A + B \varepsilon^n) \left[1 + C \ln \left( \frac{\dot{\varepsilon}}{\varepsilon_0} \right) \right] \left[1 - \left( \frac{T - T_r}{T_m - T_r} \right)^m \right]$$

Where $\sigma$ is the equivalent flow stress, $\varepsilon$ is the equivalent plastic strain, $\dot{\varepsilon}$ is the equivalent plastic strain rate, $\varepsilon_0$ is the reference equivalent plastic strain rate, $T$ is the workpiece temperature, $T_m$ is the material melting temperature, and $T_r$ is the room temperature. $A$, $B$, $C$, $m$ and $n$ are material constants.

The Johnson-Cook damage law was then presented as follows.

$$\varepsilon = \left[D_1 + D_2 \exp \left( D_3 \frac{P}{\sigma} \right) \right] \left[1 + D_4 \ln \left( \frac{\dot{\varepsilon}}{\varepsilon_0} \right) \right] \left[1 + D_5 \left( \frac{T - T_r}{T_m - T_r} \right) \right]$$

$$\omega = \sum \frac{\Delta \varepsilon}{\varepsilon_i}$$

In which, $\varepsilon_i$ is plastic strain at damage initiation, $P$ is hydrostatic pressure, $P/\sigma$ is stress triaxiality, $\dot{\varepsilon}$ is plastic strain rate, $\varepsilon_0$ is reference strain rate, $T$ is the workpiece temperature, $T_m$ is the material melting temperature, and $T_r$ is the room temperature, $D_1$-$D_5$ are damage parameters, $\omega$ is the damage parameter and $\Delta \varepsilon$ is the plastic strain increment.

Note that the damage is assumed to happen when damage parameter $\omega = 1$. Afterwards, the damage evolution was controlled by using effective plastic displacement in the FE calculation. The implementation of damage initiation and evolution ensured the complete chip separation. The input parameters for both JC constitutive model and JC damage criteria are summarized as follows: $A = 1098$ MPa, $B = 1092$ MPa, $C = 0.014$, $m = 1.1$, $n = 0.93$, $\varepsilon_0 = 1$ s$^{-1}$, $D_1 = -0.09$, $D_2 = 0.25$, $D_3 = -0.5$, $D_4 = 0.014$, $D_5 = 3.87$, respectively [15, 16].

For CFRP layer, it was modelled as isotropic but locally homogeneous. The constitutive behaviour and damage criteria of the composite phase were defined by using Hashin damage criteria [17] available in Abaqus/Explicit code. The studied CFRP material was carbon/epoxy T300/914 laminate and its material properties were summarized as follows: longitudinal modulus ($E_l = 136.6$ GPa), transverse modulus ($E_\perp = 9.6$ GPa), in-plane shear modulus ($G_{12} = 5.2$ GPa), major Poisson’s ratio ($\nu_{12}$...
longitudinal tensile strength \( (X_T = 1500 \text{ MPa}) \), longitudinal compressive strength \( (Y_T = 27 \text{ MPa}) \), transverse compressive strength \( (Y_C = 200 \text{ MPa}) \), in-plane shear strength \( (S = 80 \text{ GPa}) \) [18].

The interface part was modelled through the concept of cohesive zone. Traction-separation law with linear softening was utilized to simulate the mechanical behaviour of the cohesive interaction. Damage initiation and evolution were controlled by using BK damage law available in Abaqus/Explicit. The relevant input parameters for interface zone modelling are summarized as follows: \( K_{nn} = 2.0 \text{GPa}, \ K_{ss} = K_{tt} = 1.5 \text{GPa}, \ t_n f = 60 \text{MPa}, \ t_s f = t_t f = 80 \text{MPa}, \ G_n C = 0.78 \text{N/mm}, \) and \( G_s C = G_t C = 1.36 \text{N/mm}. \)

2.3. Validation of the stack model

For validation purpose, each stacked constituent (i.e., Ti model and CFRP model) was verified carefully through the comparisons with experimental results from open literatures due to the significant lacking of experimental studies concerning orthogonal cutting of hybrid CFRP/Ti stacks. Both Ti-layer model and CFRP-layer model were validated in terms of cutting-force comparison by refer to experimental results gained by Umbrello [19] and Iliescu et al. [20], respectively. During the validation work, the cutting conditions were selected the same used in literatures. Figure 2 shows the comparison of simulated and experimental results for both Ti-layer validation and CFRP-layer validation. It can be seen that the established models produced the consistent results with the experimental observations from open literatures [19, 20] which indicated the accurate development of the proposed numerical models. When each model was refined and improved correctly, they were assembled to perform the FE simulation of hybrid CFRP/Ti cutting.

\[ \text{Figure 2. (a) Validation of Ti-layer model with open literature [19] and (b) validation of CFRP-layer model with open literature [20].} \]

3. Results and discussion

In hybrid CFRP/Ti machining, typically two different cutting-sequence strategies (Ti\( \rightarrow \)CFRP and CFRP\( \rightarrow \)Ti) exist from the aspect of tool-entry and tool-exit throughout the chip removal process. In this section, a comparative studied focused on the different cutting-sequence strategies were performed in terms of force generation, machined surface quality and induced damage formation.

3.1. Cutting-force investigation

The cutting force generation \( (F_c) \) was studied and compared vs. cutting speed \( (v_c) \) and feed rate \( (f) \), and the obtained numerical results are shown in figure 3. In each cutting-sequence simulation, the \( F_c \) magnitudes were predicted based on individual layer cutting (i.e., Ti-phase cutting and CFRP-phase cutting) and repeated three times in order to minimize the measurement error.
As illustrated in the above figure 3, it was noticeable that the cutting-sequence strategy exhibited crucial role in affecting the cutting-force generation, irrespective of the used cutting parameters. In Ti→CFRP cutting sequence, the predicted $F_c$ in CFRP-phase cutting yielded higher values than its counterpart produced in CFRP→Ti cutting sequence. Similarly, when operated in CFRP-Ti cutting sequence, the generated cutting force of Ti-phase cutting also achieved higher magnitudes than that obtained in Ti-CFRP cutting sequence. Such physical phenomena indicated that the identical-phase cutting which operated last in one specified cutting sequence typically promoted higher cutting-force generations than that operated initially in another cutting sequence, i.e., higher Ti-force generation in CFRP→Ti cutting sequence and higher CFRP-force generation in Ti→CFRP cutting sequence as depicted in figure 3. The key mechanisms controlling the physical phenomena can be attributed to favourable effects of chip adhesions on tool rake face that contributing to the increase of cutting resistance and hence the higher force generation.

In addition, feed rate ($f$) was observed to have significant influences on the cutting-force generations in such manner that a small increase of $f$ typically resulted in great elevation of $F_c$ in both Ti-phase cutting and CFRP-phase cutting. In contrast, the cutting speed ($v_c$) was found to have negative effects on the force generation, i.e., increased $v_c$ favoured the reduction of force generation in hybrid stack cutting. The reason could be explained by the fact that increased $v_c$ typically promoted high cutting-heat generation, softened the machined workpiece and hence resulted in less cutting resistance for further chip separation removal.

### 3.2. Machined surface morphology and induced damage

To clarify the practical influence of cutting-sequence strategy on hybrid cutting process, an inspection was made through the observations of the machined surface morphology vs. different cutting-sequence strategies under the fixed cutting conditions ($v_c = 40$ m/min, $f= 0.2$ mm/rev and $\theta = 0^\circ$). Figures 4 and 5 then show the comparative numerical observations.

It can be seen that in hybrid CFRP/Ti cutting, disparate chip morphologies were generated during the entire chip separation process. Such phenomena were caused due to the dissimilar natures of the composite and metallic phases. In CFRP-phase cutting, the resected chip appeared “dust” like shape due to the brittle-fracture predominant chip-separation mode while in Ti-phase cutting, the chip shape was generated principally in the form of “continuous” appearance due to the dominated plastic-deformation mode. Moreover, the chip adhesion on tool rake face was also observed in the two cutting-sequence machining. The evidence strongly interpreted the phenomena of different force generations of identical-phase cutting under different cutting-sequence strategies (as illustrated in Section 3.1).

In addition, it was noticeable that the machined surface finish produced in CFRP→Ti cutting sequence seemed to be much smoother than that operated in Ti→CFRP cutting sequence. Moreover, only minor crack damage was detected beneath the machined CFRP surface in CFRP→Ti cutting sequence as shown in figure 4. In contrast, the Ti→CFRP cutting sequence commonly promoted serious crack imperfects concerning the CFRP-phase machined surface. Furthermore, the CFRP
surface generated in Ti→CFRP cutting sequence appeared extremely uneven and rough as compared to that obtained in CFRP→Ti cutting sequence. Such phenomena could be attributed to the serious Ti-chip adhesion on tool rake face that generating severe scratching effects on the machined composite surface.

Figure 4. Machined surface morphology and induced damage in CFRP→Ti cutting sequence ($v_c = 40$ m/min, $f = 0.2$ mm/rev and $\theta = 0^\circ$).

Figure 5. Machined surface morphology and induced damage in Ti→CFRP cutting sequence ($v_c = 40$ m/min, $f = 0.2$ mm/rev and $\theta = 0^\circ$).

With regard to the interface cutting, the damage mode occurred at the bi-material interface commonly exists in the form of delamination imperfection. In Ti→CFRP cutting sequence, typically a large length of delamination damage was produced focused on the bi-material interface. The predicted delamination length ($d_m = 178 \mu$m) was approximately 4.5 times longer than that ($d_m = 40 \mu$m) generated in CFRP→Ti cutting sequence. The reason can be explained by the fact that in CFRP→Ti cutting sequence the Ti alloy can act as the role of supporting plate in preventing CFRP laminate inflection and ensuring the stability of the tool-work interaction during the cutting operation. As a result, low extent of interface delamination was promoted. In contrast, when operated in Ti→CFRP cutting sequence, the CFRP phase could not act the role of supporting plate when tool firstly cut into the Ti phase and subsequently the interface region due to its brittle nature of the fibre/matrix system. Consequently, high extent of delamination damage was produced focused on the bi-material interface.

4. Conclusions
This paper developed an original FE model to simulate the chip formation process when cutting hybrid CFRP/Ti stacks. Different damage criteria were introduced to model the cutting behaviour of the
composite phase and metallic phase. Special FE analyses were made focused on the comparative studies of different cutting-sequence strategies and also their influences on hybrid cutting operation. Based on the acquired FE results, some key conclusions can be drawn as follows:

- The use of the cohesive zone successfully replicated the delamination phenomenon activated among the CFRP/Ti interface. The numerical model allowed the reliable prediction of the key phenomena generated in hybrid CFRP/Ti cutting.
- Feed rate had significant positive impact on the cutting-force generation when cutting hybrid composite (CFRP/Ti) stacks. However, the impact arising from cutting speed was negative due to the softening effects of cutting temperature on the work material when cutting speed increased.
- The numerical results highlighted the favourable effects of CFRP→Ti cutting sequence on reducing the force generation, minimizing the interface delamination, and consequently promoting excellent machined surface morphology when orthogonal cutting of hybrid CFRP/Ti stacks.

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