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A discrete element method for the simulation of CFRP cutting

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ABSTRACT

Orthogonal machining of unidirectional carbon fiber-reinforced polymer (UD-CFRP) composites is simulated using discrete element method (DEM). The objective of this work is to present a simple numerical model that allows the study the machining of unidirectional composites during orthogonal cutting. To control the physicochemical phenomena that occur during cutting, it is necessary to identify the parameters of contact, very difficult to measure experimentally. The DEM numerical simulation is presented then as an alternative to the problem. This tool has helped to recreate the physical mechanisms identified experimentally and to understand the origin of the abrasive wear of carbide tools. The observation of the chip formation using a high speed video camera made possible to validate qualitatively the results of numerical simulation by discrete elements. This tool can also determine the cutting forces quite close to reality.

1. Introduction

Carbon fiber-reinforced polymer composites (CFRP) materials are characterized by a combination of high properties (specific strength and stiffness, light weight, etc.), which make their use especially attractive for aircraft and aerospace applications [1]. However, CFRP machining is difficult due to their material discontinuity, inhomogeneity and anisotropic nature and to the abrasive behavior of carbon fibers. The machining process significantly affects these materials. The damage consists of various failures modes, including fiber breakage, matrix cracking, fiber–matrix debonding and plies delamination. To achieve the desired surface quality, it is necessary to understand the physical mechanisms of the material removal and the kinetics of the machining process affecting the performance of the cutting tools. Compared to metal machining, studies on composites machining are few although there is a renewed interest in recent years. Koplev [2,3] was the first in 1980 to conduct a series of experiments on CFRP orthogonal cutting. The author concluded that the chip formation is strongly influenced by the fiber orientation and occurred through a series of successive ruptures. The surface quality and the delamination factor were strongly dependent on the tool geometry and cutting forces. Crack propagation ahead of the tool tip (Mode I) was observed during machining of 0° orientation laminates, compression induced rupture was noticed during machining of 90° orientation laminates. Arola et al. [4] pointed out that the cutting of negative fiber orientation CFRP can be attributed to compression induced shear failure. For the same range of fiber orientations, Bhatnagar et al. [5] described fiber breakage due to axial tension as the cutting mechanism. In the work of Puw and Hocheng [6], a correlation between the cutting force, the length and the thickness of the chip, when the speed direction is perpendicular to the fiber orientation, was found. This correlation is based on the classical theory of beams and the theory of laminates. They suggested that the fibers break when the bending stresses exceeded the ultimate material strength. Arola and Ramulu [7] described the chip formation mechanisms during CFRP orthogonal cutting with a diamond-tipped tool. The authors explained that the chip formation is due to a brittle fracture independent of the fiber orientation. They observed from experiments that both cutting and thrust force registered a minimum in the 15–30° fiber orientation range and increased up to 90°.

Composites machining involves a great number of physical parameters, which are very difficult to measure experimentally. Thus, numerical simulation can provide valuable information to understand cutting phenomena. Relatively few studies have been developed from the last years. Some of them are macromechanical type, based on the Equivalent Homogeneous Material (EHM) assumption. These approaches predict the chip formation and sub-surface damage in the workpiece for different cutting conditions. Arola and Ramulu [7] consider the FEM as a valid approach for the orthogonal cutting of composites, although the results from ABAQUS were different from the values obtained experimentally.

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Mahdi and Zang [8] proposed a quasi-static approach using the ADINA software to study the machining of composite materials, with the tool considered as rigid, the part considered as an equivalent homogeneous anisotropic material and the friction is ignored. Zitoune and Collombet [9] proposed a static model to determine the cutting forces and to examine the state of the tensile strength σ. The FEM used is an isoparametric volume type of the SAMCEF software. Calculations follow a linear static assumption and the contact is modeled by the penalties method. A 3D finite element model using the ABAQUS software was developed by Durao et al. [10] in order to study the damage of drilling operation (especially delamination) produced on CFRP plates. The model presents a mixed mode of damage allowing delamination modeling. The main objectives were to compare the influences of the drills geometry on the damage initiation and growth. Venu Gopala Rao et al. [11] modeled the cutting of composite materials with the following assumptions: the tool is rigid, the fiber is isotropic and elastic, the matrix has an elastoplastic behavior and friction a value of 0.3. To facilitate the calculations the authors have modeled the area of the workpiece closed to the tool. The fiber/matrix interface is modeled with zero thickness and detachment by a cohesive zone model (CZM). CZM represents an approach of fracture mechanics to study the effects of interface in different materials or in the same material when they are at the beginning glued together. The temperature produced between tool and work piece is neglected. Venu Gopala Rao et al. [12] proposed a quasi-static approach based on the ABAQUS EXPLICIT software, which gives less computing time and eliminates some significant difficulties in the previous model. This code has two scales: a microscale close to the cutting zone where the fiber and the matrix are considered as two different bodies, and a macroscale away from the cutting area where the composite is modeled as an equivalent homogeneous material (EHM). The initiation and progression of damage of the matrix are also included in this study. The authors argued that the damage did not depend on the orientation of fibers and therefore it can be completely characterized by a dimensionless scalar variable. Pramanik et al. [13] used a FEM approach to study the machining of metal matrix composites. The authors used the ANSYS/LS-DYNA software (based on a Lagrangian description). Lasri et al. [14] have used a FEM approach and a homogeneous equivalent material (HEM) assumption to model orthogonal cutting of unidirectional GFRP. Chip formation process and damage modes such as matrix cracking, fiber–matrix debonding and fiber breaking were modeled by degrading the material properties. Damage analysis was carried out using Hashing, maximum stress and Hoffman failure criteria. The authors pointed out that the use of the stiffness degradation concept with the appropriate failure criterion allows predicting changes in the chip formation process for FRPs machining. However, the estimations of cutting and thrust forces showed large deviations with experimental data.

Models of discrete elements types have been initiated for geotechnical applications [15] and used later in several disciplines such as tribology [16]. Later models by discrete elements have been proposed for the study of abrasion process [17]. These models, based on a Lagrangian description, follow every particle in their movement. Particle interaction laws are the forces acting on these particles. The integration of the fundamental law of dynamic makes possible to calculate the trajectory of each particle. The use of these models in order to quantitatively simulate a real situation seems still difficult. However, they seem particularly well suited to help understand the basic physical phenomena.

In this study, the ability of DEM to simulate cutting of CFRP has been investigated. The cutting forces, contact pressure and frictional shear at the tool–fiber interface during machining of UD-GFRP composite were calculated by simulation and validated with experimental results. The objective of the present study is to develop a Discrete Element Method (DEM) to simulate the chip formation mechanism during the machining of UD-CFRP composites.

2. Simulation of composite cutting by DEM

The material behavior is defined by the micromechanical particles interaction laws. The general principle of this discrete elements model can be divided into three stages:

1. *Pretreatment*: (a) to define the field, geometry and arrangement of particles, (b) to specify the physical characteristics of the field (the mass, the particles behavior laws, the connections between particles, the criteria for failure, etc.), (c) to impose boundary conditions.
2. *Dynamic calculation:* (a) forces exerted on the particles, (b) acceleration, velocity and position of particles.
3. *Post-treatment*: (a) cutting forces (b) numerical images of the machining of unidirectional composites during orthogonal cutting.

2.1. Algorithm

To calculate the particle movement, the process involves several steps. At a given time t (step 0), each particle are defined in terms of mass, radius, position, velocity and acceleration. We can then find all existing contacts (step 1) between the spheres of the media. Each contact allows the calculation of the interactions forces between spheres (step 2). The fundamental dynamics law (Newton's law) is applied to determine the acceleration of each particle (step 3). An integration algorithm allows to determine the particle speed (step 4) and particle position (step 5) at time $t + dt$.

2.1.1. Contact search

All contacts between the different spheres are searched. We can define the presence of a contact when $O_1O_2 \leqslant R_1 + R_2$ (where O_1O_2 is the distance between the centers of two spheres, and R_1, R_2 respectively the radius). The numerical model tolerates a spheres interpenetration $\delta = R_1 + R_2 - O_1O_2$ to manage the contact. This could be understood as a deformation of spheres, even if no notion of deformable environments mechanics (elasticity, plasticity, etc.) comes into account. This interpenetration should be kept very small compared with the radius of the spheres. Three positions are taken into account between the two particles: (a) when the spheres are in contact ($\delta = 0$), (b) when they intersect ($\delta < 0$), this interaction involving tensile and compression link type between particles, (c) when they do not touch ($\delta > 0$), their behavior is only traction type. To reduce calculation time for contact search the Linked Cell Method is used [18].

2.1.2. Contact forces

Normal and tangential forces between spheres are explicit functions of the interpenetration δ and the interpenetration speed, which is the normal or tangential component of relative velocity $\dot{\delta}$ between the spheres. At the contact between two spheres, the normal interaction force $\vec{F}_n$ is written simply as the sum of two components:

$$\vec{F}_n = \vec{F}_r + \vec{F}_d \quad (1)$$

$$\vec{F}_r = -K \cdot \delta \cdot \vec{n} \quad (2)$$

$$\vec{F}_d = -2 \cdot \alpha \cdot \sqrt{K \cdot M_{eq}} \cdot \dot{\delta} \cdot \vec{n} \quad (3)$$

where $\vec{F}_r$ is the repulsion force, K is the contact stiffness, δ is the interpenetration, $\vec{n}$ is the outside normal contact, $\vec{F}_d$ is the strength