Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Composites Science and Technology 67 (2007) 2271–2281
COMPOSITES SCIENCE AND TECHNOLOGY
www.elsevier.com/locate/compscitech

Machining of UD-GFRP composites chip formation mechanism

G. Venu Gopala Rao [a], Puneet Mahajan [a], Naresh Bhatnagar [b,*]

[a] Department of Applied Mechanics, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110 016, India
[b] Department of Mechanical Engineering, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110 016, India

Received 11 August 2006; received in revised form 2 December 2006; accepted 19 January 2007
Available online 8 February 2007

Abstract

The chip formation mechanism in orthogonal machining of unidirectional glass fiber reinforced polymer (UD-GFRP) composites is simulated using quasi-static analysis. Dynamic explicit finite element method with mass scaling is used for analysis to speed up the solution. A two-dimensional, two-phase micromechanical model with elastic fiber, elasto-plastic matrix and a cohesive zone is used to simulate the debonding interface between the fiber and the matrix. The elements of the fiber are failed once the maximum principal stress reaches the tensile strength and the matrix elastic modulus is degraded once the ultimate strength is reached. The effect of fiber orientation, tool parameters and operating conditions on fiber and matrix failure and chip size is also investigated. The degradation of the matrix adjacent to the fiber occurs first, followed by failure of the fiber at its rear side. The extent of sub-surface damage due to matrix cracking and interfacial debonding is also determined.

Keywords: Composites; Material damage; Chip formation; Micromechanics; Machining

1. Introduction

The chip formation mechanism in orthogonal machining of unidirectional glass fiber reinforced polymer (UD-GFRP) composites is very different from conventional metal machining. The material is non-homogeneous and failures of both fiber and matrix contribute to the final chip formation from the work material. Various possible damage mechanisms such as fiber pullout, fiber fragmentation, delamination, matrix burning and sub-surface damage lead to poor cut surface quality in machining of fiber reinforced polymer (FRP) composites. Compared to the machining of metals, studies on machining of composites are few and limited in number. Some of the possible chip formation mechanisms in machining of UD-FRP composites have been suggested in the earlier studies [1–9]. However, all the mechanisms are shown as schematic views without a detailed discussion or simulations to support the suggested chip formation mechanism. Present study is an extension of the previous analysis by the present authors [10], where the cutting forces, contact pressure and frictional shear at the tool–fiber interface in simulation of machining of UD-GFRP composite were calculated by simulation and validated with experimental results.

The objective of the present study is to develop a Finite Element (FE) model to simulate the chip formation mechanism during the machining of UD-GFRP composites for the same material system, tool geometry and process parameters as used in the earlier study [10]. ABAQUS/Standard FE code was used earlier. However, simulations in this code are time consuming and convergence difficulties arise. Use of ABAQUS/Explicit FE code helps overcome these difficulties. The FE model has two scales: a micro-scale adjacent to the cutting zone where fiber and matrix are considered separately and a macro-scale away from the cutting zone where the composite is modeled as an equivalent homogeneous material (EHM). The EHM replaces the real two-phase material with separate matrix

* Corresponding author. Fax: +91 11 2658 2053.
E-mail address: nareshb@mech.iitd.ernet.in (N. Bhatnagar).

0266-3538/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compscitech.2007.01.025

Nomenclature

UD-GFRP	unidirectional glass fiber reinforced polymer
EHM	equivalent homogeneous material
FRP	fiber reinforced polymer
FE	finite element
CZM	cohesive zone model
$f_{1,2}$	first and second fiber respectively
$m_{1,2,3}$	first, second and third matrix respectively
V	velocity of the cutting tool
t	depth of cut
θ	fiber orientation
r	edge radius
γ	rake angle
α	relief angle
h_1	depth of sub-surface damage in the first matrix
h_2	depth of sub-surface damage in the second matrix
h_3	depth of sub-surface damage in the third matrix
h_5	height of damage above the trim plane in the second matrix
h_6	height of damage above the trim plane in the third matrix
$d_{1,2}$	damage variable at the interface in normal and shear direction
d_m	damage variable in the matrix material
D_m	damage variable matrix for the matrix material
E_e, E	elastic modulus of un damaged and damaged epoxy material
σ_e	effective stress tensor of the undamaged material
σ	nominal stress tensor of the damaged material
u_f^{pl}	equivalent plastic displacement at failure
u^{pl}	equivalent plastic displacement related to the plastic strain ε^{pl}
G_f	fracture energy per unit area dissipated during the damage process

and fiber phases by an equivalent transversely isotropic homogeneous single-phase material with properties (E_{11}, E_{22}, G_{12} and υ_{12}) determined from experiments. The fiber is considered elastic and the matrix is considered elasto-plastic with isotropic hardening. The interface between the fiber and matrix is modeled using cohesive zone elements, which allow for debonding at the interface. The initiation and evolution of damage in matrix is also included in the present study. This paper investigates the effect of fiber orientation on stresses in the fiber and its failure, the evolution of damage in the matrix, interfacial debonding leading to chip formation mechanism and also sub-surface damage. The damage initiation and evolution in the matrix is implemented based on the material yield strain and fracture energy respectively [11–14]. The element failure in the fiber is considered based on the induced maximum principal stresses.

2. Finite element formulation, damage and interfacial failure

Commercially available finite element analysis software tool ABAQUS™ version 6.5 [15] is used for simulation of chip formation mechanism in orthogonal machining of UD-GFRP composites. A plane stress formulation is used to study the machining of FRP composites. The heat generation between the cutting tool and the work material is neglected, as experiments are conducted at very low cutting speed ($V = 0.5$ m/min). In the numerical model, to keep the problem tractable, only region of the work material close to chip formation zone is modeled (2000 μm × 1000 μm). The portion of the work material adjacent to the cutting tool is modeled using fiber and matrix separately, whereas, portions away from the cutting tool are modeled as EHM. Two fibers, three matrix layers and two EHM regions as shown in Fig. 1 are considered. The tool is assumed to be in contact with the first fiber (f_1) after the first matrix (m_1) has been removed prior to machining simulation. All the fiber and matrix regions are meshed with four noded plane stress quadrilateral elements. Mesh convergence studies were performed and finally all fiber and matrix domains are modeled with approximately 1 μm × 1 μm element size. The EHM regions are modeled with combination of both four-node quadrilateral and three-node triangular elements. The three-node triangular elements are used for the mesh transition from fine to coarse mesh. The fine mesh is used in the fiber and matrix whereas coarse mesh is used in the EHM away from the fiber or matrix domain. The sizes of elements, in fine and coarse mesh domains are approximately 1 μm × 1 μm and 16 μm × 16 μm respectively. The displacements of the bottom of the work piece in both cutting and perpendicular direction are restrained ($u_x = u_y = 0$) in the FE model. The displacements of extreme left side are also restrained ($u_x = 0$) in the cutting direction. The cutting tool is modeled as a rigid body (as the elastic modulus of solid carbide cutting tool material is six times the elastic modulus of glass fiber) and a reference point controls the movement of the cutting tool. Prior experiments show that the velocity of cutting marginally affects the cutting of UD-GFRP composite [10]. It was therefore decided to consider the process as quasi-static and implement the same using ABAQUS/Explicit FE code. The FE code has provision for implementing damage initiation and evolution in matrix and debonding at the interface of fiber and matrix using cohesive elements.