

FINITE ELEMENT MODELING FOR MACHINING OF UNIDIRECTIONAL FIBER REINFORCED POLYMER COMPOSITES

By

G. VENU GOPALA RAO

DEPARTMENT OF APPLIED MECHANICS

Submitted

In fulfillment of the requirements of the degree of

Doctor of Philosophy

to the

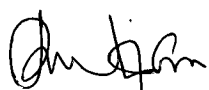


INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER, 2007

CERTIFICATE

This is to certify that the thesis entitled '**FINITE ELEMENT MODELING FOR MACHINING OF UNIDIRECTIONAL FIBER REINFORCED POLYMER COMPOSITES**' being submitted by **G. VENU GOPALA RAO** is the report of bonafide research work carried by him under our supervision. This thesis has been prepared in conformity with the rules and regulations of the Indian Institute of Technology Delhi, New Delhi. We further certify that the thesis has attained a standard required for a Ph.D degree of the institute. The research reported and the results presented in the thesis have not been submitted, in part or full to any other institute or university for the award of any other degree or diploma.



Dr. Puneet Mahajan
Professor,
Department of Applied Mechanics,
Indian Institute of Technology Delhi,
New Delhi -110016, INDIA.



Dr. Naresh Bhatnagar
Associate Professor,
Department of Mechanical Engineering,
Indian Institute of Technology Delhi,
New Delhi -110016, INDIA.

Place: New Delhi,

Date: 22-10-2007.

ACKNOWLEDGEMENTS

First of all I would like to say thanks to my supervisors ***Prof. Puneet Mahajan***, Professor, Department of Applied Mechanics, Indian Institute of Technology Delhi, India and ***Dr. Naresh Bhatnagar***, Associate Professor, Department of Mechanical Engineering, Indian Institute of Technology Delhi, India for giving me this opportunity to do my Ph. D work. Also I am very thank full to both of them for their strong cooperation and advise during my thesis work. It is needless to mention that both of them have been extremely helpful to me in providing high quality guidance and support on various facets of my research work and other situations of life at various stages. I had an immense scope of learning the best from both of them for which I sometimes consider myself lucky.

I am also very thankful to my institute (Indian Institute of Technology Delhi, New Delhi India) for providing good experimental and computational facility throughout my thesis work.

I am really thankful to all of my friends and co-research students who helped me with material, moral and intellectual support at the time of need. I would like to take this opportunity to thank all those who helped me in whatever capacity to see that the present project attains a successful completion.

I am also very thankful to my parents, for their patience and encouragement during the entire thesis work.

Last but not least, I thank GOD, the almighty, for his blessings for whatever I have and giving me inner solace and strength to overcome the ups and downs of life.


G. Venu Gopala Rao

ABSTRACT

Orthogonal machining of unidirectional carbon fiber reinforced polymer (UD-CFRP) and glass fiber reinforced polymer (UD-GFRP) composites are studied both experimentally as well as numerically. The orthogonal machining experiments are carried out on both the composites separately for a range of fiber orientations (θ), depths of cut (t) and tool rake angles (γ). The cutting (F_c) and thrust (F_t) forces are measured using piezoelectric dynamometer, chip formation process is observed and recorded using long distance optical microscope and video camera. The numerical study is done using finite element method (FEM) and it is carried out at two different scales namely macro-mechanical and micro-mechanical. First a macro-mechanical finite element (FE) model is used to simulate the machining process where the material is treated as an equivalent homogeneous material (EHM). The simulated cutting and thrust forces are correlated to the experimental observations. The cutting force from the macro-mechanical FE simulation agrees well with the experimental results. However, thrust force deviates from the experimental observations. In order to overcome this deviation of thrust force, a new two-phase micro-mechanical FE model is proposed in this research work. In the two-phase micro-mechanical FE model, fiber is assumed as elastic and matrix as elasto-plastic to estimate the cutting and thrust forces and chip formation mechanism during orthogonal machining. A bi-linear cohesive zone model (CZM) simulated the interface debonding between the fiber and the matrix. Fiber failure is based on Tsai-Wu stresses (or) in-plane maximum principal stresses reaching ultimate tensile strength of individual fiber. The damage initiation and evolution in the matrix material is implemented based on the yield strength and fracture energy respectively. The FE analysis is quasi static although explicit FE model with mass scaling is used for analysis to speed up the solution. During the FE

simulation, the induced contact pressures between the cutting tool and the fiber provided an estimate of the cutting and thrust forces. The simulated cutting and thrust forces matched well with the experimental data, thereby validating the new micro-mechanical FE model. The cutting forces vary with fiber orientation and depth of cut and the rake angle has a negligible effect on these forces. The chip formation mechanism in orthogonal machining of both UD-CFRP and UD-GFRP composites is also simulated in this study. The effect of fiber orientation, tool parameters and operating conditions on fiber and matrix failure is also highlighted. 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. The sub-surface damage is predominant due to matrix damage as compared to the interfacial debonding. The failure of fiber is found to be a combination of crushing and bending. It is concluded that the two-phase micro-mechanical FE model is more suitable in predicting the machining responses as compared to the single-phase macro-mechanical FE model.

TABLE OF CONTENTS

DESCRIPTION OF THE CONTENT	Page No.
TITLE	i
CERTIFICATE	ii
ACKNOWLEDGEMENTS	iii
ABSTRACT	iv
TABLE OF CONTENTS	vi
LIST OF FIGURES	xiii
LIST OF TABLES	xxii
NOMENCLATURE	xxiii

CHAPTER: 1

INTRODUCTION	1
1.1 Manufacturing methods	1
1.2 Development of composite materials	2
1.3 Classification of composite materials	3
1.4 Importance of FRP composites	3
1.5 Applications of polymer matrix composites	5
1.6 Motivation of research	6
1.7 Machining process	7
1.8 Finite element analysis for machining studies	8
1.9 Organization of the thesis	9

CHAPTER: 2

LITERATURE REVIEW	11
2.1 Review articles in machining of composites	11
2.2 Analytical modeling	12
2.3 Non-conventional machining of composites	12
2.4 Selection of process parameters and tool geometry	13
2.5 Experiments and numerical modeling of force and chip formation	14
2.5.1 Force analysis studies	14
2.5.2 Chip formation studies	16
2.6 Existing gaps in the knowledge	17
2.7 Objectives of the present study	18

CHAPTER: 3

SPECIMEN PROCESSING AND MACHINING EXPERIMENTS ..	19
3.1 Introduction	19
3.2 Specimen preparation for the machining experiments	19
3.3 Machining experiments	20
3.3.1 Experimental set-up	20
3.3.2 Cutting forces measurement	23
3.3.3 Chip formation mechanism and image analysis	25
3.4 Experimental observations of force data	32
3.4.1 Cutting and thrust force analysis	32
3.4.2 Effect of fiber orientation on forces	35

3.4.3 Effect of depth of cut on forces	35
3.4.4 Effect of tool rake angle on forces	36
3.4.5 Effect of type of material system on forces	36

CHAPTER: 4

MATERIAL CHARACTERIZATION	38
4.1 Introduction	38
4.2 Material constitutive relations	38
4.3 Transformations of stress and strain relations	42
4.4 Fiber volume fraction of the present material system	44
4.5 Fiber distribution in the present material system	46
4.6 Tensile properties of the present material system	47
4.6.1 Instron 5582	47
4.6.2 Instron Merlin	48
4.6.3 Dimensions of the specimen	48
4.6.4 Tabs preparation	49
4.6.5 Test conditions and results	50
4.7 Shear properties of the present material system	51
4.7.1 Specimen preparation	54
4.7.2 Testing machine and conditions	55
4.8 Summary of tensile and shear properties	55
4.9 Tensile and compressive strength properties for off-axis specimen	58
4.10 Stiffness properties for off-axis specimen	60

CHAPTER: 5

MACRO-MECHANICAL FINITE ELEMENT MODEL	62
5.1 Introduction	62
5.2 Macro-mechanical finite element formulation	63
5.2.1 Modeling details	63
5.2.2 Boundary conditions	65
5.2.3 Assumptions in the FE model	65
5.2.4 Material properties	66
5.3 Friction at the contact between cutting tool and work piece	67
5.4 Failure criteria implementation in the FE model	68
5.4.1 Critical stress failure criterion	68
5.4.2 Tsai-Wu failure criterion	70
5.5 Contact pressure and frictional shear stresses at the contact zone	71
5.6 Comparison of cutting and thrust forces from experiments and macro-model ...	73
5.7 Stress distribution in the work material	77
5.8 Chip formation mechanism	79
5.9 Sub-surface damage due to material failure	81
5.10 Short comings of the macro-mechanical FE model	82

CHAPTER: 6

MICRO-MECHANICAL FINITE ELEMENT MODEL	84
6.1 Introduction	84
6.2 Micro-mechanical finite element formulation	85

6.2.1 FE model details	85
6.2.2 Boundary conditions	89
6.2.3 Assumptions made in the micro-mechanical FE simulation	89
6.2.4 Material properties used in the FE simulation	90
6.3 Failure criteria implementation in the FE model	92
6.3.1 Damage initiation and evolution in the matrix material	92
6.3.2 Element failure implementation of the fiber (carbon and glass) material ...	95
6.3.3 Damage initiation and evolution at the fiber-matrix interface	95
6.3.4 Equivalent homogenous material failure criterion	100
6.4 Explicit dynamics and implementation of mass scaling	100
6.5 Contact pressure and frictional shear stresses from the FE simulation	104
6.6 Induced stresses in the fiber, matrix and EHM before failure	106
6.6.1 Stress variation with fiber orientation	106
6.6.2 Stress variation with depth of cut	112
6.6.3 Stress variation with material system	113
6.7 Quantitative variation of stresses in the first fiber close to the chip zone	116
6.7.1 Stresses at the rear faces of the first fiber	117
6.7.2 Stress variation across the first fiber near the chip formation zone	120
6.8 Shifting of contact zone and chip size during the simulation	122
6.9 Extent of damage in the work material above the trim plane	124
6.10 Sub-surface damage (Extent of damage below the trim plane)	125

CHAPTER: 7

RESULTS AND DISCUSSION	129
7.1 Variation of cutting and thrust forces with time from experiments	129
7.2 Comparison of forces from both experiments and micro-mechanical model	129
7.3 Discussion on cutting and thrust force variations	133
7.3.1 Effect of fiber orientation on cutting and thrust forces	135
7.3.2 Effect of depth of cut on cutting and thrust forces	136
7.3.3 Effect of tool rake angle on cutting and thrust forces	136
7.3.4 Effect of material system on cutting and thrust forces	136
7.4 Magnitude and direction of resultant force from experiments and micro-model ..	137
7.5 Mechanism of matrix failure observations	141
7.5.1 Quantitative variation of damage in the matrix	141
7.5.2 Mechanism of matrix failure for various fiber orientations	142
7.6 Extent of damage in the matrix above the trim plane	143
7.7 Mechanism of chip formation	145
7.7.1 Material damage progress during simulation	145
7.7.2 Size of the broken fiber	148
7.7.3 Damage variation with fiber orientation	150
7.8 Discussion on chip formation	153
7.8.1 Effect of fiber orientation on chip formation mechanism	153
7.8.2 Effect of depth of cut on chip formation mechanism	153
7.8.3 Effect of tool rake angle on chip formation mechanism	153
7.8.4 Effect of material system on chip formation mechanism	154

7.9 Sub-surface damage (Extent of damage below the trim plane)	155
--	-----

CHAPTER: 8

CONCLUSIONS	159
--------------------------	------------

8.1 Macro-mechanical FE model	160
-------------------------------------	-----

8.2 Micro-mechanical FE model	160
-------------------------------------	-----

8.2.1 Machining forces (cutting and thrust)	160
---	-----

8.2.2 Chip formation	161
----------------------------	-----

8.2.3 Sub-surface damage	163
--------------------------------	-----

8.3 Scope for future work	163
---------------------------------	-----

REFERENCES	165
-------------------------	------------

APPENDIX A	172
-------------------------	------------

A. CONVERGENCE STUDY (ERROR APPROXIMATION).....	172
---	-----

A1. Macro-mechanical finite element model	173
---	-----

A2. Micro-mechanical finite element model	175
---	-----

AUTHOR BIOGRAPHY	179
-------------------------------	------------

LIST OF PUBLICATIONS	180
-----------------------------------	------------
