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Machinability Study of Fibre-Reinforced Polymer Matrix Composites

By

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Abstract

The trend in the applications of advanced composite materials, namely the fibre-reinforced polymer (FRP) composites, ranges from high performance industrial products to the low end consumer goods. These composite products are commonly fabricated to near-net shapes with finishing steps that involve machining being the integral part of component manufacture. However, the composite machining becomes a challenge compared to that of the conventional metallic materials due to their inherent properties. The damage susceptibility of the FRP composites impedes the consistency of machining quality, whereas the abrasiveness of the workpiece material inflicts rapid wear on the cutting tools. As a result, extensive scientific research has been devoted to investigate the machinability of these materials in order to elucidate their fundamental machining characteristics. Although much attention on turning and drilling of FRP composites can be traced in the existing literature, only a handful of researchers have reported experimental results on limited aspects of FRP composites milling machinability indices. Hence, this thesis has embarked on a systematic machinability study of end milling glass fibre-reinforced polymer (GFRP) composites.

A design of experiment methodology was initially employed to determine the effects of machining parameters on key machinability indices or outputs and the suitable operational or machining parameters (guided by the final applications). On the basis of this parametric study, experimental investigations under a wider range of machining parameters and material characteristics were conducted. From these experiments, the empirical relationships between tool performance (in terms of tool life) and the selected parameters were analysed using the traditional Taylor’s tool life equation. The useful life of the cutting tool was found to be well described by the Taylor’s equations. The cutting speed was identified as the key parameter in influencing the tool life followed by feed rate and fibre orientation. Surface finish, on the other hand, was found to
marginally improve with a higher spindle or cutting speed, but rapidly deteriorated with the increase of feed rate. An acceptable machining quality could be achieved by machining along the fibre orientation despite a higher tool wear rate. It appears from the scanning electron microscopy that the machining induced damage comprises fibre fracture, pull-out or protrusions, delamination damage, and epoxy matrix brittle failure. All of these are attributed to the high machining force and reduction of tool sharpness.

The constitutive relationships between the growth of tool wear and the measured machining forces were also studied as a pursuit to monitor the cutting tool condition during machining operation. Although adequate agreement between experimental data can be well achieved using multiple regression analysis, the application of fuzzy logic with neural network model demonstrated a significant improvement in the prediction accuracy. Notably, the accuracies of this model are pronounced as a result of nonlinear fuzzy membership function and its hybrid learning algorithms. This makes it attractive as an indirect tool condition monitoring during the machining operation.

Machinability of GFRP composites has also been qualitatively evaluated in terms of chip forming mechanisms. This has been accomplished using a high-speed video camera and a quick-stop method. It is apparent that the heterogeneity and insufficient ductility of the composites have produced discontinuous and fracturing chips under the tested machining parameters. A layer of delaminated chip was formed (under the mild cutting speed) as the tool cutting edge fractured the workpiece material along the fibre orientation. However, the increased cutting speed and fibre orientation accelerate the fracture of chips into smaller segments, which make it difficult to denote any chip formation processes.
To:
My son, Adam Azwan,
My Wife, Norliza Katuk
And
My Parents, Azmi Othman &
Azidah Abd. Hamid
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‘Praised be to the Almighty, the most Gracious and most Merciful’

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Contents

Abstract ................................................................................................................................... i
Dedication ............................................................................................................................... iii
Acknowledgements ............................................................................................................... iv
Contents ................................................................................................................................. vi
List of Figures ........................................................................................................................ xi
List of Tables .......................................................................................................................... xviii
Nomenclature ........................................................................................................................ xxi
Glossary of Terms ................................................................................................................ xxi

Chapter 1 Introduction .......................................................................................................... 1
  1.1 Background ..................................................................................................................... 1
  1.2 Machinability of Composite Materials ........................................................................ 2
  1.3 Research Objectives ...................................................................................................... 4
  1.4 Thesis Outline ............................................................................................................... 5

Chapter 2 Literature Review ................................................................................................. 7
  2.1 Fibre-Reinforced Polymer (FRP) Composites .............................................................. 7
      2.1.1 Preface .................................................................................................................. 7
      2.1.2 Types and forms of fibre reinforcement ............................................................... 8
      2.1.3 Polymer matrix ................................................................................................... 10
2.1.4 Manufacturing and processing of FRP composites ............................... 12
2.2 Machining as Secondary Processes for FRP Composites ....................... 16
2.3 Assessment of Machinability for FRP Composites ............................... 19
2.4 Review of Previous Studies on Conventional Machining of FRP composites .................................................................................. 22
  2.4.1 Drilling of FRP composites ......................................................... 22
  2.4.2 Turning and orthogonal cutting of FRP composites .................... 29
  2.4.3 Milling of FRP composites ....................................................... 36
2.5 Cutting Tool for Milling FRP Composites ........................................... 41
  2.5.1 Tool materials ........................................................................ 41
  2.5.2 Cutting tool geometry ............................................................ 43
2.6 Dry Machining of FRP Composites .................................................. 44
2.7 Tool Condition Monitoring during Machining .................................... 44
2.8 Soft Computing Modelling of Machinability Performance .................. 51

Chapter 3 Experimental Procedure .................................................. 58
  3.1 Fabrication of GFRP Composite Specimens .................................... 58
    3.1.1 Selection of fibre reinforcement and matrix material .................. 58
    3.1.2 Manufacturing of test panels ............................................... 59
    3.1.3 Fabrication procedure ........................................................ 60
    3.1.4 Specimen characterisation methods ...................................... 62
    3.1.5 Scanning electron microscopy ............................................. 66
  3.2 Experimental Equipment and Procedure ....................................... 69
    3.2.1 CNC milling machine .......................................................... 69
    3.2.2 Data acquisition equipment and procedure ......................... 71
    3.2.3 Selection of cutting tool ...................................................... 77
  3.3 Summary .................................................................................... 80
Chapter 4 Parametric Study of GFRP Composites Machining ... 81

4.1 Introduction ........................................................................................................ 81

4.2 Design of Experiments .................................................................................... 82

  4.2.1 Taguchi method ......................................................................................... 82

  4.2.2 Experimental layout and selection of machinability parameters .......... 83

4.3 Results and Discussion .................................................................................... 86

  4.3.1 Evaluation of significant factors through statistical analyses .............. 90

  4.3.2 Interpretations and discussion on the parametric/factorial effect ......... 98

4.4 Validation Test of Desirable Settings .......................................................... 110

4.5 Concluding Remarks ....................................................................................... 112

Chapter 5 Regression Analyses of Tool Performance .............................. 114

5.1 Introduction ..................................................................................................... 114

5.2 Experimental Parameters ............................................................................. 115

5.3 Results and Discussion .................................................................................. 118

  5.3.1 Results of tool wear growth .................................................................... 118

  5.3.2 Variations of machining forces .............................................................. 134

5.4 Force Dependent Flank Wear Relationships .............................................. 140

  5.4.1 Simple regression of tool wear – machining force relationships .......... 143

  5.4.2 Multiple regression of tool wear – machining force relationships .. 144

5.5 Concluding Remarks ..................................................................................... 150

Chapter 6 Fuzzy Logic Analyses for Tool Condition Monitoring151

6.1 Introduction .................................................................................................... 151

6.2 Prediction and Monitoring of Tool Wear using ANFIS Model ............... 153

  6.2.1 Background of Fuzzy Logic or Fuzzy Inference System ................. 153

  6.2.2 Architecture of ANFIS ........................................................................... 154
Appendix 3-3: SGS 41665 end milling tool basic specifications ......................... 209

Appendix 4-1: Supplementary data for the measured $F_y$ and $F_z$ from the L9 Taguchi experiments ................................................................. 210

Appendix 4-2: Supplementary data for Taguchi L9 analyses ...................... 211

Appendix 5-1: Effects of machining at different fibre orientation on tool wear growth for cutting speed of 190 m/min (5,000 RPM) and feed rate of 0.24 mm/rev. ................................................................. 214

Appendix 5-2: SEM micrographs of worn cutting tool for various machining parameters .................................................................................. 215

Appendix 5-3: Regression output for Taylor’s tool life equation generated from Microsoft Excel Data Analysis Toolbox ................................. 216

Appendix 5-4: Supplementary predicted data from Eqs. 5.4-5.5 for the tested parameters ................................................................................ 217

Appendix 5-5: Supplementary results on repeated experiments at the specified machining parameters .......................................................... 219

Appendix 5-6: Supplementary results of machining force variations .......... 221

Appendix 5-7: Regression outputs for tool wear-machining forces regression analyses generated from Microsoft Excel Data Analysis Toolbox ................................................................................ 223

Appendix 5-8: Normal probability plots from regression analyses ............ 224

Appendix 5-9: Supplementary results of MRA predicted versus experimental data for selected machining parameters .......................................... 225

Appendix 6-1: Generated fuzzy rules from ANFIS models ....................... 227

Appendix 6-2: Final Gaussian MFs after ANFIS training .......................... 228

Appendix 6-3: Supplementary results of checking datasets ...................... 229

Appendix 7-1: Static images of chip formation ........................................ 230

REFERENCES ............................................................................. 231
List of Figures

Figure 2.1: Continuous, woven and random/short chopped fibres ......................... 8
Figure 2.2: Epoxide group ..................................................................................... 10
Figure 2.3: A molecule of (a) diglycidyl ether of bisphenol A (DGEBA) epoxy resin and (b) diethylene triamine (DETA) curing agent [1, 2] .................... 11
Figure 2.4: (a) Formation of cross linking and (b) three dimensional network structure of solid epoxy [1, 2] ............................................................... 11
Figure 2.5: Schematic of wet hand lay-up process [4] ............................................ 13
Figure 2.6: Basic of RTM [5] ................................................................................ 14
Figure 2.7: Stages of resin infusion or VARTM [4] ............................................... 15
Figure 2.8: Typical material damage mechanisms in FRP composites as a result of machining forces (a) In-plane damage and (b) delamination [26] ......... 20
Figure 2.9: Various modes of delamination during carbon fibre-reinforced polymer (CFRP) composites cutting [27, 28] ....................................................... 21
Figure 2.10: Classification of delamination during drilling of FRP composites [30] 23
Figure 2.11: Delamination damage at the entrance and exit of the drilled FRP composites [31] ................................................................................................. 23
Figure 2.12: Circular plate model for delamination analysis of FRP composites [32] ............................................................................................................. 24
Figure 2.13: Decomposition of total thrust force, $F_z$ [34] ..................................... 25
Figure 2.14: Cutting edge rounding (CER): (a) sharp cutting edge and (b) blunt smoothly worn, rounded cutting edge [29] ................................................. 28
Figure 2.15: Flank wear versus time of alumina cutting tools for machining GFRP composites [82] ......................................................................................... 32
Figure 2.16: Cross-section of specimens showing mechanisms of chip formation leading to machining induced damage for (a) cutting parallel and (b) perpendicular to fibre [9] .................................................................34

Figure 2.17: End milling of rectangular workpiece material........................................36

Figure 2.18: Development of cutting tool materials and their achievable cutting speed in the various machining operations [127] .........................................................41

Figure 2.19: Toughness and hardness of tool materials, HW-tungsten carbide, CA-alumina ceramics, CN-nitride ceramics, BN-boron nitride, PD/DP-polycrystalline diamond [126] ...........................................................42

Figure 2.20: Microstructure of WC-Co material, WC grains appear as the dark phase and the cobalt binder a lighter colour [3] .................................................................42

Figure 2.21: Cutting tool geometry for milling FRP composites (a) straight flute router, (b-d) single helix and (e-f) multiple helix tool and burr tool [3] ..............................................................................................................................43

Figure 2.22: Classification of statistical and soft computing techniques for modelling of machining research [152] .........................................................................................52

Figure 2.23: A schematic drawing of a biological neural network [153] .......................52

Figure 2.24: A feedforward neural network ................................................................53

Figure 3.1: Close-ups of the E-glass reinforcement ....................................................59

Figure 3.2: Schematic diagram of VARTM ...............................................................60

Figure 3.3: Dry compaction of the preform prior to resin infusion ...........................61

Figure 3.4: GFRP plate for the end milling experiments ............................................62

Figure 3.5: Tensile strength data for different batches of laminates produced ..........63

Figure 3.6: The electrical furnace used for the burn-off test showing test specimens (a) before and (b) after experiment .................................................................64

Figure 3.7: Fibre volume fraction data for different batch of laminates produced ...65

Figure 3.8: The FEI Quanta 200F and prepared GFRP samples for SEM characterisation .................................................................67

Figure 3.9: SEM images of cross-sectioned composite laminates ...........................68

Figure 3.10: Schematic diagram of overall machining experiments set-up ..............69

Figure 3.11: The CNC machine centre with Centroid controller .............................70
Figure 3.12: Full immersion cutting with up cut and down milling action of the cutting tool (cross-section view) ........................................................... 70

Figure 3.13: (a) Force measurement directions on the dynamometer and (b) Kistler® charge amplifier and PC with LabVIEW® for data acquisition .......... 71

Figure 3.14: Machining force region during a single end milling pass ................. 73

Figure 3.15: Typical criterion used for measurement of flank wear, VB [170] ....... 74

Figure 3.16: Leica MZ16 optical stereo microscope for tool wear measurement ..... 75

Figure 3.17: Taylor Hobson Surtronic-3 surface measurer used for $R_a$ measurement ........................................................................................................ 76

Figure 3.18: Top view of the composite laminate for illustration of $R_a$ measurement ........................................................................................................ 76

Figure 3.19: $R_a$ measurement for the reference specimen ............................... 77

Figure 3.20: Toughness and hardness of four major families of tool materials [3].. 78

Figure 3.21: The uncoated tungsten carbide end mill tool used for this experiment. 79

Figure 3.22: SEM images of the end mill tool ......................................................... 79

Figure 4.1: Measured $R_a$, $F_x$ and calculated $F_m$ from the L9 DOE experiments ...... 88

Figure 4.2: Optical microscope photos of typical tool wear growth and the curve of tool wear growth against machining time for experimental parameters of $A_2B_1C_3$ ................................................................................................. 89

Figure 4.3: Tool wear curves from all tests of the L9 DOE experiments .............. 90

Figure 4.4: (a) Response graph and (b) Pareto ANOVA for $R_a$ based on S/N ratio 92

Figure 4.5: (a) Response graph and (b) Pareto ANOVA for $F_m$ based on S/N ratio 94

Figure 4.6: (a) Response graph and (b) Pareto ANOVA for TL based on S/N ratio 96

Figure 4.7: Effect of changing feed rate on surface roughness, $R_a$ at different spindle speeds ......................................................................................... 99

Figure 4.8: Effect of changing spindle speed on surface roughness, $R_a$ at different feed rates ......................................................................................... 100

Figure 4.9: Geometry of an end mill tool [183] ....................................................... 101

Figure 4.10: Cutting mechanism of FRP composites [3, 111, 120] ...................... 102

Figure 4.11: SEM images of fractured fibres on the milled surface for the machining parameters of (a) $A_1B_1C_1$ and (b) $A_3B_3C_1$ ......................................................... 102
Figure 4.12: SEM images of the machined surface for the machining parameters of (a) $A_2B_2C_1$ and (b) $A_2B_3C_2$ ................................................................. 103

Figure 4.13: Orthogonal cutting chip formation and end milling chip formation diagrams ......................................................................................... 103

Figure 4.14: Chipping and cutting edge rounding on the cutting tool for machining parameters of (a) $A_1B_3C_3$ and (b) $A_2B_1C_3$ ........................................... 105

Figure 4.15: Contact and rubbing actions between the fibres and each cutting flutes (a) as the tool rotates and cuts across the fibres at the centre position and (b) close up view of central position [173] ................................... 106

Figure 4.16: SEM images showing tool wear mechanisms from the end milling tests at the respective machining parameters .............................................. 107

Figure 4.17: SEM images of chip characteristics from the end milling test........... 109

Figure 4.18: Example of EDS analysis on the rake face of end mill tool ($X$ is location of EDS scan, see Figure 4.16 (f))......................................................... 109

Figure 4.19: SEM images of validation experiments at desirable setting of $A_1B_3C_1$ ............................................................................................................. 112

Figure 5.1: Two fibre orientations employed ........................................................ 117

Figure 5.2: SEM images of (a-b) abrasive wear, (c) edge rounding and (d) micro-chipping on the cutting tool after the end milling tests ................. 119

Figure 5.3: Effects of changing cutting speed with constant feed rate of: (a) $f_r$ of 0.16 mm/rev, (b) $f_r$ of 0.24 mm/rev and (c) $f_r$ of 0.32 mm/rev on tool wear growth ......................................................................................... 120

Figure 5.4: Effects of changing feed rate with constant cutting speed of: (a) $v$ of 110 m/min, (b) $v$ of 150 m/min, (c) $v$ of 190 m/min and (d) $v$ of 230 m/min on tool wear growth ................................................................. 122

Figure 5.5: Effects of changing fibre orientation, $A$ at different machining parameters of: (a) $f_r$ of 0.16 mm/rev, (b) $f_r$ of 0.32 mm/rev, (c) $v$ of 150 m/min and (d) $v$ of 230 m/min on tool wear growth ......................................................... 123

Figure 5.6: Tool-fibre interface/contact at the centre of the cutting when tool feed direction was along the fibre orientation, $x$ ......................................... 124

Figure 5.7: Tool-fibre interface/contact at the centre of the cutting when tool feed direction was across the fibre orientation, $x$ ......................................... 125

Figure 5.8: Comparison of cutting damage when machining (a) along and (b) across fibre orientation ................................................................................... 126

Figure 5.9: Improved machinability (surface quality) using a back-up plate....... 127
Figure 5.10: SEM images of machined wall surface with sharp tool at cutting speed, \( v \) of 110 m/min and feed rate, \( f_r \) of 0.16 mm/rev.................................127

Figure 5.11: SEM images of machined wall surface for different machining parameters and fibre orientations.........................................................128

Figure 5.12: Variations of TL with respect to changing cutting speeds, \( v \) and feed rates, \( f_r \)........................................................................................129

Figure 5.13: Variations of TL with respect to changing cutting speeds, \( v \), feed rates, \( f_r \) and fibre orientations, \( A \).........................................................................130

Figure 5.14: Variations of predicted and experimental TL when end milling along the fibre direction at different cutting speed and feed rate........133

Figure 5.15: Tool wear growth from validation experiments of: (a) Test_1 and (b) Test_2, respectively.................................................................133

Figure 5.16: Variation of (a) feed force, \( F_x \), and (b) cutting force, \( F_y \), with machining time for feed rate, \( f_r \) of 0.24 mm/rev .........................134

Figure 5.17: Variations of (a) feed force, \( F_x \), and (b) cutting forces, \( F_y \), with respect to changing feed rate at constant cutting speed, \( v \) of 110 m/min ......136

Figure 5.18: Variations of (a) feed force, \( F_x \), and (b) cutting forces, \( F_y \), with respect to changing feed rate at constant cutting speed, \( v \) of 230 m/min......136

Figure 5.19: Variations of (a) feed force, \( F_x \), and (b) cutting forces, \( F_y \), with respect to changing cutting speed and fibre orientation at constant feed rate, \( f_r \) of 0.16 mm/rev .................................................................138

Figure 5.20: Variations of (a) feed force, \( F_x \), and (b) cutting forces, \( F_y \), with respect to changing cutting speed and fibre orientation at constant feed rate, \( f_r \) of 0.32 mm/rev .................................................................138

Figure 5.21: Comparison of machining forces magnitude at two fibre orientations (sharp tool) ........................................................................139

Figure 5.22: Chip formation mechanism during orthogonal cutting of FRP composites [3, 111, 120]..............................................................................139

Figure 5.23: Tool wear growth and variation of (a) feed force, \( F_x \), and (b) cutting force, \( F_y \).......................................................................................142

Figure 5.24: Individual regression results for (a) feed force, \( F_x \), and (b) cutting force, \( F_y \), for the respective machining parameters ......................143

Figure 5.25: Comparison of experimental and predicted data from MRA at (a) \( v \) of 150 m/min, \( f_r \) of 0.16 mm/rev and (b) \( v \) of 190 m/min, \( f_r \) of 0.24 mm/rev ........................................................................146
Figure 5.26: Comparison of experimental and predicted data from MRA at (a) $v$ of 150 m/min, $f_r$ of 0.16 mm/rev and (b) $v$ of 190 m/min, $f_r$ of 0.24 mm/rev

Figure 5.27: Ratio of predicted values against experimental data for (a) feed force, $F_x$ and (b) cutting force, $F_y$

Figure 5.28: (a) Scatter diagram of MRA predicted values against experimental data for (a) feed force, $F_x$ and (b) cutting force, $F_y$

Figure 6.1: The working cycle of fuzzy logic or FIS

Figure 6.2: A simple two input-single output ANFIS architecture

Figure 6.3: The first order Takagi-Sugeno fuzzy inference model

Figure 6.4: Flow of the hybrid learning procedure for the ANFIS model [202]

Figure 6.5: The implemented ANFIS architecture

Figure 6.6: Gaussian membership/activation function for ANFIS

Figure 6.7: Grid partitioning of two inputs ($A$ and $B$) with three MFs

Figure 6.8: Data and clusters in the two dimensions input space for feed and cutting force datasets

Figure 6.9: Initial Gaussian MFs prior to neural network training

Figure 6.10: Flowchart of ANFIS development phases

Figure 6.11: Converging of ANFIS training error for $ANFIS_F_x$ and $ANFIS_F_y$ respectively

Figure 6.12: Comparison of the predicted tool wear from ANFIS and MRA models with the experimental data using feed force, $F_x$ (for different cutting speeds and a constant feed rate, $f_r$ of 0.24 mm/rev)

Figure 6.13: Comparison of the predicted tool wear from ANFIS and MRA models with the experimental data using cutting force, $F_y$, (for different cutting speeds and a constant feed rate, $f_r$ of 0.24 mm/rev)

Figure 6.14: Comparison of the predicted tool wear from ANFIS and MRA models with the experimental data from the checking datasets.

Figure 6.15: Scatter diagrams of predicted values against experimental data for (a) $MRA_F_x$, (b) $MRA_F_y$, (c) $ANFIS_F_x$ and (d) $ANFIS_F_y$

Figure 6.16: 3D surface diagrams of (i) MRA and (ii) ANFIS predicted data superimposed with the experimental data for feed force, $F_x$, at (a) $f_r$ of 0.16 mm/rev and (b) at $v$ of 150 m/min
Figure 6.17: 3D surface diagrams of (i) MRA and (ii) ANFIS predicted data superimposed with the experimental data for cutting force, $F_y$, at (a) $f_r$ of 0.24 mm/rev and (b) at $v$ of 150 m/min .......................... 179

Figure 7.1: General setup on milling machine that consists of (a) Phantom V210 high-speed video camera and (b) high intensity headlights ....................... 185

Figure 7.2: (a) Side end milling of GFRP for filming of chip formation process and (b) modified end mill cutter .......................................................... 186

Figure 7.3: (a) Quick-stop arrangement on the milling machine, (b) the fitted trip switch and (c) pneumatic ram ............................................................. 188

Figure 7.4: Frames from video footage during chip formation of side end milling GFRP composites at $s$ of 100 RPM, $f_r$ of 0.32 mm/rev and $A$ of 0° .... 190

Figure 7.5: SEM images of machined surface and segmentation of chip collected at fibre orientation, $A$ of 0° and $s$ of 100 RPM, $f_r$ of 0.32 mm/rev........... 191

Figure 7.6: Frames from video footage during chip formation of side end milling GFRP composites at $s$ of 300 RPM, $f_r$ of 0.32 mm/rev ....................... 191

Figure 7.7: SEM images showing fibre-matrix debonding as a result of stress exerted on the chip by the cutting action ............................................. 192

Figure 7.8: (a) SEM images of morphologies of the collected chip while cutting at 90° to fibre orientation, (b) close-up of fractured fibres and (c) sticking-out of fibre from machined surface .............................................. 194

Figure 7.9: SEM images of chip root obtained from quick-stop method SEM images of chip root obtained from quick stop method for (a-b) $s$ of 300 RPM, $f_r$ of 0.32 mm/rev and $A$ of 0°; (c) $s$ of 500 RPM, $f_r$ of 0.32 mm/rev and $A$ of 0° and (d) $s$ of 500 RPM, $f_r$ of 0.32 mm/rev and $A$ of 90°. ................................................................. 196
List of Tables

Table 2.1: Common types, forms and arrangements fibre reinforcements .......... 8
Table 2.2: General chemical compositions and properties of glass fibres [1-3] ..... 9
Table 2.3: General properties of cured epoxy resin at 23 °C [1, 2] ..................... 12
Table 2.4: Properties of aerospace metal alloys and FRP composites [1, 2, 7, 8] . 17
Table 2.5: Machinability criteria and its definition [3, 19, 25] ............................ 20
Table 2.6: Summaries of reported literature on milling of FRP composites ......... 40
Table 2.7: Direct and indirect tool wear measurement and condition [130, 132] .. 47
Table 2.8: Overview of selected past reported research on tool condition monitoring using various sensors for different workpiece material ...... 49
Table 2.9: Summary of artificial neural network and fuzzy logic modelling employed during machining of FRP composites as reported in past research .......................................................... 56
Table 3.1: Specifications of fibre reinforcement and thermosetting resin .......... 59
Table 3.2: Average value of important properties for the GFRP panels .......... 64
Table 3.3: Sensitivity settings for the Kistler® 5001 charge amplifier ................. 72
Table 3.4: Specifications of the end mill tool ..................................................... 79
Table 4.1: Experimental parameters and their levels ....................................... 85
Table 4.2: Parametric combinations for the L9 end milling trials ..................... 85
Table 4.3: Experimental results for $R_a$, TL and $F_m$ with their corresponding $S/N$ ratios ............................................................... 91
Table 4.4: Response table for $R_a$ based on $S/N$ ratio .................................. 93
Table 4.5: ANOVA results for $R_a$ based on $S/N$ ratio .................................. 93
Table 4.6: ANOVA results for $F_m$ based on S/N ratio ................................................. 94
Table 4.7: Response table for $F_m$ based on S/N ratio .............................................. 95
Table 4.8: ANOVA results for TL based on S/N ratio .................................................. 96
Table 4.9: Response table for TL based on S/N ratio .................................................. 96
Table 4.10: Summaries of preferred setting for each machinability performance ... 97
Table 4.11: Results of validation experiment ............................................................. 110
Table 4.12: Comparison of experimental and predicted results at desirable setting ................................................. 111

Table 5.1: Machining parameters employed for full factorial experimentation ... 116
Table 5.2: Validation tests parameters ................................................................. 133

Table 6.1: The range of input and output values used during ANFIS training and validation prior to normalisation ................................................................. 161
Table 6.2: Summaries of output parameters after ANFIS training and fuzzy inferencing ............................................................................................................. 167
Table 6.3: Statistical comparisons of the MRA and ANFIS predictive performance ............................................................................................................. 175
Table 7.1: Machining parameters for chip formation studies ................................ 184
Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi_f$</td>
<td>Fibre Diameter</td>
</tr>
<tr>
<td>$E_c$</td>
<td>Young’s Modulus</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Coefficient of Thermal Expansion</td>
</tr>
<tr>
<td>$K$</td>
<td>Thermal Conductivity</td>
</tr>
<tr>
<td>$V$</td>
<td>Poisson Ratio</td>
</tr>
<tr>
<td>$G_{IC}$</td>
<td>Inter-laminar Fracture Toughness</td>
</tr>
<tr>
<td>$F_c$</td>
<td>Critical Thrust Force</td>
</tr>
<tr>
<td>$F_z$</td>
<td>Thrust Force</td>
</tr>
<tr>
<td>$F_y$</td>
<td>Cutting Force</td>
</tr>
<tr>
<td>$F_f$</td>
<td>Feed Force</td>
</tr>
<tr>
<td>$F_m$</td>
<td>Resultant Force</td>
</tr>
<tr>
<td>$R_c$</td>
<td>Centre Line Average Roughness</td>
</tr>
<tr>
<td>$f_r$</td>
<td>Feed Rate per Revolution</td>
</tr>
<tr>
<td>$f_t$</td>
<td>Feed Rate per Tooth</td>
</tr>
<tr>
<td>$s$</td>
<td>Spindle Speed</td>
</tr>
<tr>
<td>$v$</td>
<td>Effective Linear Cutting Speed</td>
</tr>
<tr>
<td>$d_c$</td>
<td>Depth of Cut</td>
</tr>
<tr>
<td>$A$</td>
<td>Fibre Orientation</td>
</tr>
<tr>
<td>$R$</td>
<td>Tool Nose Radius</td>
</tr>
<tr>
<td>$F_d$</td>
<td>Delamination Damage</td>
</tr>
<tr>
<td>$V_f$</td>
<td>Volume Fraction</td>
</tr>
<tr>
<td>$VB$</td>
<td>Flank Wear</td>
</tr>
<tr>
<td>TL</td>
<td>Tool Life</td>
</tr>
<tr>
<td>$S/N$</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>$TW$</td>
<td>Tool Wear Machining Force Relationship</td>
</tr>
</tbody>
</table>
# Glossary of Terms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>FRP(s)</td>
<td>Fibre-Reinforced Polymer Composites</td>
</tr>
<tr>
<td>MMC(s)</td>
<td>Metal Matrix Composites</td>
</tr>
<tr>
<td>SiO₂</td>
<td>Silicon Dioxide</td>
</tr>
<tr>
<td>SiC</td>
<td>Silicon Carbide</td>
</tr>
<tr>
<td>DOE</td>
<td>Design of Experiment</td>
</tr>
<tr>
<td>ANFIS</td>
<td>Adaptive Network-Based Fuzzy Inference System</td>
</tr>
<tr>
<td>RTM</td>
<td>Resin Transfer Moulding</td>
</tr>
<tr>
<td>VARTM</td>
<td>Vacuum-Assisted Resin Transfer Moulding</td>
</tr>
<tr>
<td>TiN</td>
<td>Titanium Nitride</td>
</tr>
<tr>
<td>TiC</td>
<td>Titanium Carbide</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>Titanium Alloy</td>
</tr>
<tr>
<td>PEEK</td>
<td>Poly-Ether-Ether-Ketone</td>
</tr>
<tr>
<td>GFRP</td>
<td>Glass Fibre-Reinforced Polymer</td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon Fibre-Reinforced Polymer</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Model</td>
</tr>
<tr>
<td>HSS</td>
<td>High Speed Steel</td>
</tr>
<tr>
<td>PCD</td>
<td>Poly Crystalline Diamond</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscopy</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
<tr>
<td>WC</td>
<td>Tungsten Carbide</td>
</tr>
<tr>
<td>AE</td>
<td>Acoustic Emission</td>
</tr>
<tr>
<td>MRA</td>
<td>Multiple Regression Analysis</td>
</tr>
<tr>
<td>ANN</td>
<td>Artificial Neural Network</td>
</tr>
<tr>
<td>AI</td>
<td>Artificial Intelligence</td>
</tr>
<tr>
<td>GA</td>
<td>Genetic Algorithm</td>
</tr>
<tr>
<td>MLP</td>
<td>Multi-Layer Perceptron</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>RBF</td>
<td>Radial Basis Function</td>
</tr>
<tr>
<td>MF</td>
<td>Membership Function</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>EDS</td>
<td>Energy Dispersion X-Ray Spectroscopy</td>
</tr>
<tr>
<td>CVD</td>
<td>Chemical Vapour Deposition</td>
</tr>
<tr>
<td>OA</td>
<td>Orthogonal Array</td>
</tr>
<tr>
<td>BUE</td>
<td>Built Up Edge</td>
</tr>
<tr>
<td>MAPE</td>
<td>Mean Absolute Percentage Error</td>
</tr>
<tr>
<td>RMSE</td>
<td>Root Mean Square Error</td>
</tr>
<tr>
<td>cov.</td>
<td>Coefficient of Variation</td>
</tr>
<tr>
<td>$R^2$</td>
<td>Coefficient of Correlation</td>
</tr>
</tbody>
</table>
Chapter 1 Introduction

1.1 Background

Advanced composite materials have been continuously engineered for a wide spectrum of mechanical, physical and functional performance. Indeed, their properties are still being customised to the specific industrial and consumer product requirements. With a number of breakthroughs in processing and fabrication techniques, novel composite materials offer various advantages in applications where high performance is necessary. Among many types of composite materials, fibre-reinforced polymer (FRP) composites have been attractive and extensively used. As a matter of fact, conventional metallic materials have been largely substituted by FRP composites in many cases. Typical examples of FRP composites’ applications include aerospace components (e.g. tails, wings, fuselages), racing car bodies and chassis, sporting goods (e.g. bicycle frames, surf/snow boards), and marine parts (e.g. hulls, decks). Easy processability and cheap raw materials cost make them applicable for the aforementioned structural and functional requirements.

FRP composites are notably known to be lighter, stronger, stiffer, and have a better corrosion resistance over the metal alloys and their metal matrix composites (MMCs) counterparts. Their appealing properties can also be deliberately tailored to improve fire resistance, thermal and electric insulation as well as sound absorption. These make them desirable for non-structural products, in areas, such as the panel or acoustic wall applications. Despite their excellent physical and mechanical performance, FRP composites are known for their inherently poor machinability compared to that of monolithic materials.
1.2 Machinability of Composite Materials

In common occurrence, many engineering components made from FRP composites are manufactured to near-net shapes. In spite of this, finishing steps that involve machining are essential to meet the desired dimensional requirements and/or to improve the geometrical tolerances of a previously formed shape. Furthermore, in conjunction with advances in design techniques, intricately shaped composite products or components can only be attained through machining processes.

However, as the machining process is mostly performed at the final stage of composites manufacturing, proper care is required to fulfil the machining qualities and productivities. Very often, it is inappropriate to associate the cutting mechanisms or theories obtained from homogenous materials with those for FRP composites. This is due to the inherently non-homogeneous microstructure as well as pronounced anisotropy of these materials. Thus, fundamental understandings of FRP composites machining can be adequately accomplished by performing controlled machining tests under turning, drilling or milling processes. Despite the difference in cutting mechanisms, these machining processes have a common aspect of removing a portion of material from the workpiece in the form of chip creation. This is normally achieved through the relative movement between the cutting tool and the workpiece material using either a single or multiple-point cutting edges or tools.

Regardless of the cutting tool types and machining processes used, the principal challenge of successful machining for FRP composites lies in their susceptibility to damage and delamination when subjected to extreme machining conditions. In fact, the properties of FRP composites create difficulties in machining them with consistent quality. This restricts their final usage as machined components. Since the FRP composites contain highly abrasive fibre reinforcements, they account for severe wear and premature failure of a cutting tool while machining such materials. This necessitates frequent tool changes or re-sharpening, which results in high tooling and machining costs. Deterioration of tool sharpness also increases the likelihood of inducing damage to the FRP composites, which adds to their existing poor machinability. Clearly, each of
these difficulties must be overcome through a combination of suitable selections of machining parameters, tool geometry, tool material as well as machining strategies.

A number of scientific studies on FRP composites machining have been carried out since the inception of their wide use in the late 1970s. Renewed research interests in the recent years have rigorously laid fundamental insights into the cutting mechanisms of FRP composites. The studies cover a range of experimental trials and simulations; and the results are presented using analytical, numerical, and statistical modelling. It appears that a considerable number of empirical and analytical results, particularly on turning and drilling processes, have substantially contributed towards the scientific findings on FRP composites machining. Optimal designs of new tooling and studies on the influences of machining parameters, while drilling and turning, have been treated comprehensively. Machining induced-delamination and damage detecting techniques for the aforesaid machining processes have also been extensively improved.

Evidence from literature shows that the main thrust of research undertaken globally has put significant attention on turning and drilling of FRP composites, yet, only a limited amount of work has considered milling process. As the understanding of machinability for drilling and turning has matured, the focus of research must now switch to the more complex milling operation. Since the use of FRP composites is finding tremendous increase in a wide range of applications, one can expect broader industrial applications of milling such materials. Hence, this thesis describes an elaborate study of end milling FRP composites. This machinability study is specifically performed on the uni-directional glass fibre-reinforced polymer (GFRP) composites using a tungsten carbide cutting tool.

The challenge of this research lies mainly in the complexity of the cutting mechanisms associated with milling. As the cutting actions in milling involve a tool with single or multiple edges rotating about a fixed axis, the material removal process is intermittent. This promotes periodic contact stresses, temperature and heat variations on the cutting tool and workpiece material. Each of the cutting tool edges also experiences cyclic loading during machining, as the tool fractures through different layers of fibre reinforcement and matrix materials in the composite. Under certain machining
parameters, the fluctuated loadings on the tool edges may easily change the cutting mechanisms from that of continuous machining (like in turning operation).

1.3 Research Objectives

The primary aim of this research is to undertake a comprehensive machinability study of FRP composites. The focus is on the end milling operation, in which a thorough understanding of cutting mechanisms and tooling performance are carried out. This is achieved through a series of objectives outlined as follows:

In the first part of the main work, comprehensive experiments are conducted to investigate and understand the effects of machining parameters on key machinability outputs using experimental design methodology. The suitable sets of operational conditions are established to yield desirable end milling of GFRP composites under different machinability outputs, namely surface roughness, machining forces and tool wear/life.

Until recently, many previous studies on milling FRP composites have focused on limited aspects of machinability indices, such as surface quality and machining induced damage. Nonetheless, there has been little effort to correlate the tool performance with machining parameters. Hence, the second part of this study attempts to establish the constitutive relationships between end milling parameters, GFRP composite characteristics and the machinability output, namely, the tool wear. Experiments are systematically performed over a broader range of machining parameters, and predictive models are developed using different techniques. Various machining parameters are used to validate the proposed models.

The nature of chips and their formation mechanisms during a cutting operation govern the extent of tool wear, machining force, surface quality, and sub-surface integrity. Therefore, the final phase of this research programme aims to investigate the chip formation mechanisms during milling of GFRP composites. This is achieved via photographic images of chip formation, which are recorded using a high-speed video
camera. The chip forming mechanism is also studied in terms of microscopic images of the ‘chip root’ obtained from the ‘quick-stop method’.

1.4 Thesis Outline

This first chapter of the thesis provides the introduction and motivation to the research study. The details of subsequent chapters are organised according to their contents, which are summarised as follows:

Chapter 2 presents literature search on the state of the art of FRP composites machining. It covers different aspects of FRP workpiece materials, cutting tool materials and their geometries as well as the machining test approaches and their processing conditions. The early part of the chapter provides an essential overview of the FRP composites, namely the fibre reinforcements and polymer matrices. Their processing methods are also briefly discussed. Finally, the chapter compares different techniques of modelling the machinability of these composites.

Chapter 3 elaborates the experimental procedure, namely the material selection and fabrication technique for the GFRP test panels. Material characterisations, which include mechanical testing, burn-off experiments, and scanning electron microscopy, are presented. The chapter continues with discussion and elaboration of the machining set-up, equipment, data acquisition procedure, and the cutting tool used for this research.

Chapter 4 identifies the effects of machining parameters on key machinability outputs, namely surface roughness, machining forces and tool wear/life. The importance of machining parameters is examined thoroughly using Taguchi design of experiment (DOE) and statistical analyses. Finally, a set of preferable end milling parameters is established to obtain the optimal performance of different machinability requirements or performance.
Taylor’s tool life model, considering a wider range of machining parameters, is derived in Chapter 5. The model is also extended to take into account the effect of fibre orientation on the tool wear/life. These empirical models can be used to predict the useful life of the end mill tool during machining of GFRP composites. In addition to the Taylor’s models, this chapter attempts to demonstrate the pursuit for an indirect monitoring on the extent of tool wear using the measured machinability output. The constitutive relationships between tool wear and the machining forces (with a broader range of cutting parameters) are modelled using multiple regression analysis.

For the purpose of developing an effective and accurate tool wear predictive model, a fuzzy logic analysis coupled with neural network learning capabilities, is proposed in Chapter 6. The fundamentals of neural network and fuzzy logic analyses are initially discussed, followed by elaboration on procedures or algorithms in developing the predictive model. Then, the predictive capabilities of the adaptive network-based fuzzy inference system developed in this chapter are statistically evaluated and commented upon.

Chapter 7 centres around the chip formation study to tie together the machinability assessment carried out in this doctoral research. It is primarily to gain insights into the mechanics of chip removal during end milling of GFRP composites. The results present the footage of phenomenological changes on the nature of chip formed during the cutting operation recorded using a high-speed video camera. Besides that, the microscopic studies of chip and its root gathered from the quick-stop procedures characterise the nature of chip segmentations and morphologies.

The last chapter, Chapter 8, concludes and summarises the contributions and principal accomplishments of this research study. Then, the thoughts for possible areas of expansion or avenues for any future research are also expressed.
Chapter 2 Literature Review

This chapter reviews the state of the art for FRP composites machining. The subjects vary from the types of machining operations, the effects of machining parameters, the tool geometries and materials as well as the methods of machinability analyses. Nonetheless, it is essential at the beginning of this chapter to provide related background on FRP composites. This includes the types of fibre reinforcements, polymer matrices and the FRP composites fabrication processes. Finally, a range of discussion on the optimisation and modelling of machinability performance for these composite materials concludes the last sections of this chapter.

2.1 Fibre-Reinforced Polymer (FRP) Composites

2.1.1 Preface

The use of FRP composites, as seen in the past few decades, covers a wide spectrum of applications, ranging from high-performance aerospace components to the low end consumer goods. The extensive growth in their applications stems from the increase need in the global market for high-performance and lightweight products or components. This is partially due to the substantial surges of the energy prices in the last few years, which have challenged industries to design and manufacture products and components that have a significant weight reduction. By a simple definition, a composite material comprises at least two phases: the reinforcing phase and the matrix or binding phase. The aforesaid definition can represent any general classification of a material in the microscopic level. This may include metals alloys, plastics and their co-
polymers, woods, and other minerals. However, from a macroscopic point of view, FRP composites constitute in-homogeneous and anisotropic properties, which are totally different compared to that of metal alloys and the non-reinforced polymer properties.

2.1.2 Types and forms of fibre reinforcement

It is well known that FRP composites are fabricated through combinations of fibre reinforcements and matrix materials that give a range of favourable physical and mechanical properties. These properties are usually different to the individual components quite significantly and are often governed by the types, the forms as well as the directions or arrangements of the fibre reinforcements. The choice of appropriate fibre type generally depends on the performance and the functional requirements, apart from the processing techniques involved. The continuous and woven fibres are mostly recommended for structural applications, whereas the random short fibres are suitable for non-structural applications. Table 2.1 and Figure 2.1 illustrate the forms, types and arrangements that FRP composites can have.

Table 2.1: Common types, forms and arrangements fibre reinforcements

<table>
<thead>
<tr>
<th>Types/Material</th>
<th>Form</th>
<th>Possible Arrangement</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-Glass</td>
<td>Long continuous</td>
<td>Uni-directional fibres</td>
</tr>
<tr>
<td>Carbon</td>
<td>Woven</td>
<td>Multi-directional fibres</td>
</tr>
<tr>
<td>Aramid/ Kevlar*</td>
<td>Random short/chopped</td>
<td>Random discontinuous fibres</td>
</tr>
</tbody>
</table>

Figure 2.1: Continuous, woven and random/short chopped fibres
Fibre reinforcements are designed to be the principal load-carrying constituents. They provide key structural properties such as high specific-strength and stiffness to the composite material. A single fibre typically has a diameter in the range of 5 μm to 20 μm, depending on the types. As a result, the fibre is flexible and can easily confirm to various shapes prior to processing [1]. The fibre reinforcement used during the course of this study is the glass fibres, which are common to FRP composites. On the basis of their chemical composition and manufacturing cost, glass fibres can be classified into two types, namely the E-glass and S-glass, Table 2.2.

Glass fibres are notably known for their low cost and high tensile strength. They are particularly attractive due to their high chemical resistance and excellent insulation properties. However, the limitations of these fibres are mostly due to its’ relatively low tensile modulus and high density in comparison to other fibres such as carbon and Kevlar®. The glass fibres are also sensitive to abrasion during handling because of its high hardness [2]. As the main thrust of research continues to be undertaken globally and the technology has become available, new classes of E-glass fibres are constantly introduced alongside their improved fabrication techniques. Properties of FRP composites can, therefore, be engineered for superior mechanical performance as compared to any known materials.

<table>
<thead>
<tr>
<th>Type</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>B₂O₃</th>
<th>Na₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-glass</td>
<td>54.5</td>
<td>14.5</td>
<td>17</td>
<td>4.5</td>
<td>8.5</td>
<td>0.5</td>
</tr>
<tr>
<td>S-glass</td>
<td>64</td>
<td>26</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Properties</th>
<th>E-glass</th>
<th>S-glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre Diameter, Φ (μm)</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>2.54</td>
<td>2.50</td>
</tr>
<tr>
<td>Young’s modulus, Eₜ (GPa)</td>
<td>Parallel to fibre axis</td>
<td>70</td>
</tr>
<tr>
<td>Tensile strength (GPa)</td>
<td>3.45</td>
<td>4.50</td>
</tr>
<tr>
<td>Elongation at break (%)</td>
<td>4.8</td>
<td>5.7</td>
</tr>
<tr>
<td>Coefficient of thermal expansion, α (10⁻⁶ K⁻¹)</td>
<td>Parallel to fibre axis</td>
<td>6</td>
</tr>
<tr>
<td>Thermal conductivity, k (W/m K)</td>
<td>0.59–1.8</td>
<td>1.1–1.4</td>
</tr>
<tr>
<td>Poisson’s ratio, ν</td>
<td>0.2</td>
<td>0.22</td>
</tr>
</tbody>
</table>
2.1.3 Polymer matrix

Polymer matrix in the FRP composites ensures that the fibres maintain their desired location and orientation within the composite material. The matrix also acts as a load transfer medium between the fibres, although only a small portion of load can be sustained by it. Finally, it offers protection to the fibre reinforcement from any environmental changes such as crack propagation from fibre to fibre, which could cause catastrophic failure of the composite materials. In order to meet the aforesaid functions, polymer matrices must possess the following properties: (1) it should be low-viscous liquid capable of converting into a durable, tough solid, and (2) it should be able to impregnate the fibres to form strong adhesive bonds between them. Commonly used polymer materials either commercially or in research studies came from thermosetting polymer such as epoxy, vinyl ester, polyester, phenolics. Nevertheless, some thermoplastics materials are recently being introduced for FRP composites fabrication, which include polyether-ether-ketone (PEEK), polyamide, and polycarbonate.

Among different thermoset and thermoplastic resins, epoxies are widely used for FRP composites manufacturing due to several distinct properties. Epoxies have excellent adhesion to a wide variety of fibres and other substrates, apart from its’ high-corrosion resistance to chemicals and solvent. It is also non-volatile and versatile in processing. In general, epoxy is a liquid resin that consists of monomers or short chain polymers with an epoxide group (one oxygen atom and two carbon atoms) located at either end of the molecule chains, Figure 2.2. Polymerisation or cross-linking (known as curing reaction) takes place by mixing the resin with a curing agent (hardener) to form covalent bonds between the molecules.

![Figure 2.2: Epoxide group](image)

Such an example of epoxy resin and curing agent (hardener) are diglycidyl ether of bisphenol A (DGEBA) and diethylene triamine (DETA), Figure 2.3 (a) and (b) respectively [1, 2]. During the polymerisation, hydrogen atoms in the amine (NH₂) groups of a DETA molecule, for instance, react with the epoxide groups (of the DGEBA
molecules) to cross-link with each other. The cross-linking forms three dimensional network structures as depicted Figure 2.4 (b). This structure is stiffer, stronger, but less ductile compared to that of thermoplastics [3]. Although curing of resin at ambient temperature is common, the rate at which the resin forms a rigid or solid three-dimensional network of epoxy polymer structure can often be controlled. Frequently used method to control the cross-linking rate is through temperature settings and selection of proper mixing ratio. To assist with an accurate mixing of epoxy resin and hardener for cross-linking, manufacturers usually formulate a simple mix ratio of each component that can be easily achieved by measuring the weight or volume.

![Figure 2.3](image1.png)

(a)

(b)

Figure 2.3: A molecule of (a) diglycidyl ether of bisphenol A (DGEBA) epoxy resin and (b) diethylene triamine (DETA) curing agent [1, 2]

![Figure 2.4](image2.png)

(a)

(b)

Figure 2.4: (a) Formation of cross linking and (b) three dimensional network structure of solid epoxy [1, 2]
Table 2.3 exhibits some of the general physical and mechanical properties of cured epoxy resin at 23 °C as reported in [1, 2].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, (g/cm³)</td>
<td>1.2 – 1.3</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>55 – 130</td>
</tr>
<tr>
<td>Tensile modulus (GPa)</td>
<td>2.75 – 4.10</td>
</tr>
<tr>
<td>Poisson ratio, ν</td>
<td>0.2 – 0.33</td>
</tr>
<tr>
<td>Coefficient of thermal expansion (10⁻⁶ m/m per °C)</td>
<td>50 – 80</td>
</tr>
<tr>
<td>Thermal conductivity, k (W/m K)</td>
<td>0.2</td>
</tr>
<tr>
<td>Cure shrinkage (%)</td>
<td>1 – 5</td>
</tr>
</tbody>
</table>

2.1.4 Manufacturing and processing of FRP composites

The basic building block of FRP composites manufacturing is the arrangement of a number of fibre layers to create a preform. Depending on design requirements, the arrangement of the preform can be uni-directional type, where all fibres arrange in one direction, or multi/bi-directional for continuous (long) woven types of fibre reinforcements. On the other hand, whenever discontinuous (short) fibre reinforcements are used, the arrangement is usually uni-directionally or randomly oriented. Very often, the manufacturing processes designed for FRP composites are different compared to that of conventional processes used for metals, although in some cases, similarities can be found with processing of polymers.

In general, fabrication of FRP composites requires significantly less energy and lower pressure or force than the manufacturing processes employed for metals. Net-shape or near-net shape manufacturing with parts integration in order to reduce or eliminate finishing operations, are common to FRP composites manufacturing. Until recently, several processing techniques have been developed to fabricate the composite material with a uniform fibre and matrix distribution. These processes include pultrusion, prepreg production, filament winding, and liquid composite moulding. It is not the intention of this section to describe each one of them, hence, the manufacturing process described herein is directly related to the one employed during the course of this study.
As a comparison, this section proceeds with a brief description on one of the most basic fabrication processes, namely the wet hand lay-up.

(A) Wet hand lay-up
In the early days, wet hand lay-up was the dominant process to fabricate FRP composites. It is still currently being used to make prototype or composite parts due to the available knowledge and experience of handling this process. Figure 2.5 depicts the schematic of wet hand lay-up process, in which liquid resin is applied to fibre reinforcement that are initially placed or arranged onto an open mould type. A roller is conveniently used to distribute the liquid resin throughout the fibre reinforcement surface. This is also carried out to ensure the full impregnation of the resin into the dry fibre or preform.

![Figure 2.5: Schematic of wet hand lay-up process [4]](image)

To meet the required thickness, the composite part is built up by applying a series of reinforcing fibres and liquid resin layers. Once resin impregnation completes, the part is normally left to cure or solidify at a room temperature. Even though the wet hand lay-up is most common and simplest form of FRP composites fabrication, quality control (e.g. volume fraction) of this process is often difficult. It always becomes a challenge to maintain consistent quality (in terms of minimal voids and high fibre contents) of the composite parts since the process is highly dependable on the skills of the operator or worker. Thus, over the past years, researchers and manufacturers have explored the use
of closed mould processing as alternatives in improving the FRP composites manufacturing. Among which includes sheet and bulk moulding compound, compression moulding, and liquid composite moulding processes.

(B) Resin transfer moulding

Resin transfer moulding (RTM) is the family of liquid composite moulding processes. This process has been gaining interest among manufacturers and researchers in the last few years due to the improved composite part manufacturing. The process utilises a closed mould operation, in which dry preforms are placed in between two rigid mould half, Figure 2.6. The injection of liquid resin through an inlet to fill the mould and the opening of mould for part removal once the resin is fully cured complete the RTM process cycle.

One of the RTM processes, which offers cost-effective production of structural parts in medium to high volume using low-cost tooling, is the vacuum-assisted resin transfer moulding (VARTM) or simply known as resin infusion. In VARTM, a single classic rigid mould is used along with a sealed flexible bag for the other side of the mould. The flexible mould allows the application of vacuum pressure to shape the preform, while at the same time provides the driving force to flow the liquid resin throughout the fibre reinforcements.
Figure 2.7 illustrates a basic resin infusion process, which comprises three basic phases [4]:

1) **Pre-filling.** In this stage, the vacuum pressure compact the dry preform and the inlet gate is closed to equilibrate pressure in the mould cavity.

2) **Filling.** The filling phase is initiated by opening the inlet gate. The resin is sucked from the resin pot to impregnate the preform under the vacuum pressure.

3) **Post-filling.** Once the preform is completely impregnated with resin, the inlet gate is closed and the soaked preform is allowed to cure during the post-filling phase.

Summarising on some of literature related to RTM, it is well documented that VARTM offers numerous advantages over other composite fabrication methods, particularly the wet hand lay-up. Since the top half mould is made of flexible vacuum bag, the tooling cost is significantly reduced when compared to the traditional rigid-mould of the RTM process. Apart from that, this process often improves repeatability, which results in consistent quality of manufactured parts [4]. Consequently, VARTM becomes more attractive for manufacturing of large-scale composite components such as those used in the marine industries.

It is worthwhile to mention that better quality laminates, e.g. less porosity with higher fibre volume fraction, is possible due to the closed moulding operation and application
of vacuum pressure during fabrication [6]. Room temperature processing and curing, cleaner fabrication environments (less volatile gas emissions during fabrication) and complex part geometries are among other advantages of VARTM. Hence, VARTM has the potential to be one of the preferred methods for ‘large-scale’ manufacturing of composite parts in various industries for the years to come. It is to be noted here that the details of resin infusion process, e.g. raw materials, procedure and equipment, employed during the course of this study for composite part fabrications are further elaborated in forthcoming chapter, Chapter 3.

2.2 Machining as Secondary Processes for FRP Composites

Having reviewed the basics of FRP composites, this and the subsequent sections are devoted to presenting the literature pertain to FRP composites machining. Prior to that, Table 2.4 compares some of the physical and mechanical properties of aerospace metal alloys and FRP composites. It is apparent that both metal alloys and FRP composites exhibit excellent mechanical and physical properties, which make them attractive for high-performance applications. Nevertheless, judging from their strength to weight ratio (specific strength and modulus), the FRP composites demonstrate remarkable superiority to that of the metal alloys. They have essentially replaced those metal alloys in applications where weight reduction of components or parts is imperative, as highlighted in the earlier section.

Despite these outstanding mechanical performances, FRP composites are known for their inherently poor machinability. Apparently, comprehensive and widespread research interests into improving the machinability of these materials can be traced in the last few decades. These have been demonstrated through the continuous increase of scientific research findings in the literature database. It is well known that many engineering components made from FRP composites are manufactured near to their net-shape. Nonetheless, secondary processes that involve machining are necessary to meet the required dimensional and geometrical tolerances.
Table 2.4: Properties of aerospace metal alloys and FRP composites [1, 2, 7, 8]

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Tensile Strength (MPa)</th>
<th>Tensile Modulus (GPa)</th>
<th>Thermal Cond. (W/mK)</th>
<th>Max. Ope. Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerospace Metal Alloy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>4.43</td>
<td>950</td>
<td>113.8</td>
<td>6.7</td>
<td>315</td>
</tr>
<tr>
<td>Inconel 718</td>
<td>8.22</td>
<td>1350</td>
<td>200</td>
<td>11.4</td>
<td>650</td>
</tr>
<tr>
<td>Al 7075-T6</td>
<td>2.81</td>
<td>572</td>
<td>71.7</td>
<td>130</td>
<td>-</td>
</tr>
<tr>
<td>Uni-Directional FRP composites</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass/Epoxy (45%)</td>
<td>1.81</td>
<td>870</td>
<td>39.5</td>
<td>1.44</td>
<td>80-215</td>
</tr>
<tr>
<td>Carbon/Epoxy (61%)</td>
<td>1.59</td>
<td>1730</td>
<td>142</td>
<td>-</td>
<td>80-215</td>
</tr>
<tr>
<td>Kevlar®/Epoxy (53%)</td>
<td>1.35</td>
<td>1100</td>
<td>63.6</td>
<td>-</td>
<td>80-215</td>
</tr>
</tbody>
</table>

FRP composites such as the glass fibre-reinforced polymer, consists of fibre reinforcements, which are in-homogenously mixed with polymer resins. With such composition, achieving and maintaining the required machining qualities become a challenge if improper machining parameters are selected. As a matter of fact, during machining, the fibres take a proportion of load to promote a series of fibre fractures and brittle failures of the matrix material [9, 10]. These failures serve to reduce plastic deformation for proper chip formations, which normally seen during metal cutting. This increases the likelihood of inducing machining damage, which consists of various failure modes such as delamination, sub-surface damage, and fibre-matrix debonding [10].

On top of that, the fibre reinforcement contains silicon dioxide or silicon carbide elements, SiO₂/SiC (having hardness value in the range of 500 – 700 HV [11]), which are highly abrasive. This will rapidly accelerate the wear on the cutting tools at a rate higher to that of metals and their alloys during machining. This is particularly true for conventional machining processes such as turning, drilling, or milling, which involve a direct contact of the cutting tool with the FRP composites during cutting. The operating window to machine or cut the FRP composites is also limited to the types of tools employed due to the low thermal conductivity of fibres and matrix resin.
On the basis of the aforesaid difficulties, nonconventional machining processes, which include water/abrasive water jet machining, laser machining and ultrasonic machining, have been attempted in the past by several researchers [12-18]. Despite being noncontact and less sensitive to FRP composites properties, nonconventional approaches have been quite ineffective for rapid removal of material. Nonconventional approach is also incapable of inducing substantial shape changes on the workpiece material, as it is by the conventional machining methods [19]. The experience and knowledge of handling conventional tools, as opposed to high investment cost of machine tools, may deter the applications of nonconventional processes for machining FRP composites in the main stream industries.

Machinability studies of FRP composites, through conventional methods, have produced useful and fundamental information, for practical or industrial applications. Indeed, a comprehensive review of previous research results have been given in several reports [3, 20-23]. These research studies have progressed from experimental approaches, to analytical and numerical methods as well as to statistical modelling of FRP composites machining. Notwithstanding this, the amounts of published reports in relation to milling operations are still relatively small, even though being one of the most employed machining processes in industry.

The lack of research interest or attention to milling FRP composites could likely be due to the complexity of this machining process. Milling is an intermittent cutting process performed by rotating multi point cutting tool. During the cutting operation, the uncut chip thickness varies as each tooth passes from a minimum, at the initial engagement of the tool into the workpiece material, and reaches a maximum at the centre of the cutting. The chip thickness then reduces to the minimum at the tool disengagement. These mechanisms promote periodic contact stresses and temperature variations on the cutting tool to cause premature failure. All of these enhance the existing poor machinability of the FRP composites.

Due to the relatively straightforward cutting mechanisms associated with turning, most of past research studies have considered this approach to pursue the fundamental understandings on the FRP composites machinability. Obviously, a substantial amount
of research results have reported, hitherto, the drilling of these composites. This is primarily due to the need to produce holes in the workpiece material for component assembly purposes. However, the inter-laminar damage or delamination has become the main constraint to meet the quality of FRP composites drilling.

2.3 Assessment of Machinability for FRP Composites

*Machinability* is a term often used to describe the ease or difficulty, with which, a given material or a group of materials with similar properties can be machined [24]. In particular, it is a measure of how easy or demanding it is, to cut the workpiece material with a cutting tool. It can also be defined as a measure of a resultant “property” from machining processes which affected directly or indirectly by the machining parameters. These include machining parameters, workpiece materials, tool materials and geometries, machine tool, and cutting fluids [24]. Referring to the published literature related to machinability of engineering materials, classifications of machinability can be divided into; *easy-to-machine* or *difficult-to-machine* materials.

Research studies on metal cutting have shown that machinability criteria can be defined by quantitative or qualitative terms with a single material may have more than one criterion. However, it is imperative to note that a given material may exhibit excellent machinability by one criterion, but poor by another. The most common ones that have been taken as a yardstick by researchers to evaluate the machinability of materials are tabulated in Table 2.5. These criteria are normally defined for metal cutting, but can be directly applied for non-metal such as FRP composites with some care particularly for the surface finish or surface quality.

It is essential to highlight here that due to the actions of machining forces, FRP composites exhibit a number of material damage or machining induced damage, which would not be normally observed during machining of metallic material. These types of damage include delamination, sub-surface damage, fibre pullout, fibre bridging, spalling, and matrix cracking [26]. Various modes of delamination, previously proposed in [27, 28] are depicted in Figure 2.8 and Figure 2.9 respectively. As a result, the surface
finish evaluations during machining of FRP composites have to be stringent in order to portray the correct representations of machining quality.

Table 2.5: Machinability criteria and its definition [3, 19, 25]

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machining forces</td>
<td>Forces acted on the cutting tool which can be measured by a force dynamometer.</td>
</tr>
<tr>
<td>Tool wear</td>
<td>The amount of volume lost in the tool material as a result of interactions and friction between the tool and workpiece material. In some cases, permanent deformation of cutting edges causing undesirable changes in the cutting edge geometry.</td>
</tr>
<tr>
<td>Tool life</td>
<td>A gradual failure of cutting tools due to machining operation. If the tool has worn by a certain standard amount, it can be considered as failed or unacceptable.</td>
</tr>
<tr>
<td>Taylor’s tool life model</td>
<td>Standard representation for tool life testing is given by $vTL^n = C$, where $v$ is the cutting speed, $TL$ is the tool life and $c$ is constant.</td>
</tr>
<tr>
<td>Surface quality</td>
<td>Surface integrity and texture associated with alteration of surface layer and surface micro-geometry.</td>
</tr>
<tr>
<td>Chip formation</td>
<td>Chip formed during machining and its influence on the cutting tool.</td>
</tr>
</tbody>
</table>

Figure 2.8: Typical material damage mechanisms in FRP composites as a result of machining forces (a) In-plane damage and (b) delamination [26]
Figure 2.9: Various modes of delamination during carbon fibre-reinforced polymer (CFRP) composites cutting [27, 28]
2.4 Review of Previous Studies on Conventional Machining of FRP composites

It has been reported that conventional machining processes are generally acceptable in machining the FRP composites. This is true as long as the machining parameters and the cutting tools (geometry and material) are appropriately chosen. The following reviews examine different machining operations employed for machinability studies of these materials. Special emphases are laid on tool wear data, wear rates, and the machining induced damage on the FRP composites, whenever appropriate.

2.4.1 Drilling of FRP composites

Drilling is the most frequently used machining process for composite materials owing to the need to produce holes for subsequent assembly operations of FRP components. As a matter of fact, Raraz et al. pointed out that as many as 55,000 holes are required to be drilled in a single unit production of an Airbus A350 aircraft FRP composites parts [29]. This further emphasised the necessity of drilling FRP composites. Reviews of literature reveal that drilling induced damage of the composite materials are of a more concern to that of tool wear or the tool life. In spite of this, experimental studies with regard to the performance of various tool materials and geometries during drilling of these composites have been well documented too.

(A) Drilling induced damage and surface quality

Drilling induced damage such as delamination or inter-laminar failure has been recognised as one of the major problems in FRP composites drilling by almost all researchers worldwide. Two delamination damage mechanisms associated with drilling of these composites have been regularly mentioned in the literature. These mechanisms are known as the ‘peel up’ delamination at the drill entrance and the ‘push-down’ delamination at the drill exit, Figure 2.10. Apparently, contact between the cutting edge of the drill bit and the composite laminate generates a peeling force in the tool axial direction through the slope of the drill flute [30]. The cutting flutes tend to pull the upper laminae to cause the material to spiral upward instead of being sheared. As a result, the upper laminae can easily be separated from the uncut portion to cause
delamination on the top of laminate surface [30]. As the drill tip approaches the end of laminate during drilling, the uncut material thickness reduces, which promotes severe deformation. At some point, the stress caused by the thrust force exceeds the inter-laminar strength of the FRP to induce exit delamination as the tool pierces through the material [30].

![Diagram of delamination during drilling of FRP composites](image)

Figure 2.10: Classification of delamination during drilling of FRP composites [30]

Delamination is known to be more severe at the bottom-most surface plies (exit position of the hole) of the composite, Figure 2.11. Nonetheless, both mechanisms result in the reduction of structural strength and poor assembly tolerance. This delamination phenomenon has the potential for long-term performance deterioration of the FRP components. Very often, this becomes the limiting factor for widespread applications of drilled composites [30].

![Images of delamination damage at entrance and exit](image)

Figure 2.11: Delamination damage at the entrance and exit of the drilled FRP composites [31]
It has been well documented that thrust force (being primarily a function of feed rate and tool geometry) is the main cause of delamination during drilling of FRP composites. Referring to the earlier statement, delamination is initiated as the thrust force exceeds a threshold value of the composite inter-laminar strength at the critical entry and exit locations of the drill bit or tool. Based on literature, the reported work by Hocheng and Dharan are considered to be the pioneering efforts in mathematical modelling of peel up and push out delamination of the hole entry and exit [32]. These models correlate the onset delamination with respect to the critical thrust force, which was developed according to the linear elastic fracture mechanics (LEFM) with classical plate bending theory, Figure 2.12.

![Figure 2.12: Circular plate model for delamination analysis of FRP composites [32]](image)

The critical thrust force at the onset of delamination during tool entrance is given as:

\[
F_{C}^{*} = k_{p} \pi \left[ \frac{8G_{IC}E(H - h)^{3}}{3(1 - v^{2})} \right]^{1/2}
\]

Whereas, critical load at the onset of crack propagation during tool exit can be calculated as:

\[
F_{A}^{*} = \pi \left[ \frac{8G_{IC}E(h)^{3}}{3(1 - v^{2})} \right]^{1/2}
\]

Where \(G_{IC}\) is the inter-laminar fracture toughness in Mode I, \(E\) is the elastic modulus, \(v\) is the Poisson ratio of the material, and \(k_{p}\) is the peeling factor. Jain et al. extended the aforesaid models by incorporating a variable feed rate strategy to minimise delamination [33]. In another study [34], the authors suggested that loading stress
distributions on the chisel edge, $F_{z1}$ and principal edge (lip of the drill), $F_{z2}$ result in total thrust force, $F_z$, which can be given as $F_z = 2F_{z1} + F_{z2}$, Figure 2.13.

Figure 2.13: Decomposition of total thrust force, $F_z$ [34]

Summarising on the literature with regard to drilling induced damage of FRP composites, it can be seen that a considerable amount of contributions in this field have been recently undertaken by Tsao and Hocheng [35-55]. Analytical models with experimental validations on the effect of various drill bits of different geometries and designs have been modelled and tested. The respective critical thrust force values for the onset of the exit delamination have been comprehensively developed by them. The authors also demonstrated the effects of chisel edge and a pilot-hole drilling toward the critical thrust force and the resulting delamination damage in a few research publications [37, 44, 47, 52].

In spite of this, different work on modelling the FRP composites which have been introduced and developed by other researchers can be found in [33, 56-59]. The work of these authors have incorporated different fibre reinforcement characteristics, tool geometries, use of back-up plate, and adaptive feed control or feed rate strategy. These research studies have been carried out experimentally and validated using numerical simulations (e.g. finite element analysis, FEA) [34, 60, 61]. The progresses on the different techniques in measuring delamination damage have also been reported [10, 40, 62-64]. This includes destructive and non-destructive examinations such as Ultrasonic C-Scan, X-ray, digital analysis, computerised tomography, dye-penetration, and shadow moiré laser based imaging approach.
(B) Tool wear and tool performance

Over the years, different tool materials have been tested to evaluate their performance and to elucidate the wear mechanisms during drilling of FRP composites [65]. With respect to this, the number of holes being drilled through or the drilling distance is more of a concern to indicate the machinability performance. Nevertheless, some researchers have used the total drilling time as a yardstick to evaluate cutting tool capability. Most of the published literatures have identified that abrasive wear to be the dominant tool wear and tool failure mechanism during drilling of FRP composites. It is vital to note here that abrasive wear is associated with the presence of hard SiO₂ or SiC elements in the fibre reinforcement. This material, which under high cutting pressure between the tool flank face and the workpiece material, would indent into the tool and micro-cut tiny groves in the tool surface [3].

It has been reported, in a study by Malhotra [66], that the occurrence of both chisel edge and flank wear on high speed steel (HSS) and carbide tool during drilling of carbon epoxy composite laminate. This was observed at a relatively low spindle speed of 1,250 RPM and feed rate of 60 μm/rev. As reported, carbide drills were found to outperform the HSS tools, (with respect to drilling time), even under these low or mild parameters. Under relatively similar cutting parameters, Ramkumar et al. experimentally evaluated the performance of uncoated and titanium nitride and titanium carbide (TiN/TiC) coated HSS tools during drilling of glass fibre epoxy composites [67]. Their results showed that the coated drills wear rapidly beyond only a certain number of holes. This was mainly attributed to the peeling or chipping of the coating from the substrate material [67].

Murphy et al. compared the performance of coated and uncoated tungsten carbide drills, during drilling of carbon fibre epoxy composites [68]. The results revealed that the coatings did not provide any significant improvement on the tool life of the tungsten carbide tool either. Weinert and Kempmann attributed this to tribological behaviour, low fracture toughness and a relatively weaker interlayer adhesion of the coating to the cemented carbide substrate material [69]. Since the uncoated tungsten carbide tool can be used to drill FRP composites under normal cutting parameters with a reasonable success, Lin and Chen [70] attempted an ultra high speed of up to 38,000 RPM to drill
CFRP composites. Aggressive tool wear was still found to be problematic while drilling at such speeds using standard twist and multifaceted drill bits. However, acceptable hole entry and exit qualities were claimed to be maintained due to mild feed rate employed [70].

In a recent study, Rawat and Attia have confirmed the dominant influence of spindle or cutting speed on the tool life during drilling of FRP composites through their employed Taylor's tool life equation [65]. They also observed a steady increase of tool wear rate in the primary and the tertiary wear regions which strongly influenced the thrust force to cause severe delamination on the composite materials. The correlations between tool wear, delamination damage and surface roughness have been established in the authors’ work [65].

On the basis of FRP composites being poor thermal conductors, a reduction of cutting-zone temperature through the application of coolants or by improving the tool conductivity can enhance its machinability [10]. In Ref [10], Bhattacharyya et al. reported such study during drilling of Kevlar® composites. Higher thrust force was generated while drilling at cryogenic temperature, which augmented the likelihood of delamination. However, the results demonstrated a substantial improvement in tool life of the modified HSS drill bits [10]. With regard to this, the authors claimed that a higher tool life can defer the inception of push-down delamination. A suggestion was put forward that regardless of the conditions, delamination can be minimised by using a back support, which is industrial common practice.

(C) Other recent advances in drilling FRP composites

Although abrasive wear on the tool flank face has been well known to be the dominant tool wear mechanism of drilling FRP composites, a new wear feature which is based on the change or increase in cutting edge rounding (CER) magnitude has been studied in the past. Raraz et al. initially proposed this new wear feature while drilling CFRP composites [29]. The ‘optical interference fringe projection microscopy’ was used to accurately and precisely measure the 3D profilography of the cutting tool edge.
Comparisons in the form of the different magnitudes of the cutting edge rounding of a drill bit, as reported in their study, are illustrated in Figure 2.14 [29]. The authors claimed that measurement of the CER-based wear on an individual cutting edge for various drill bits was much easier and accurate to that of conventional wear on the flank face. In fact, the relationships between mechanical loads and CER, as well as the relationships between the hole entry/exit delamination and the CER were claimed to be well correlated. In spite of this, their results were confined to constant drilling parameters; hence, varying these values may produce different wear mechanisms.

Changing the machining strategy from conventional uni-axial drilling to multi-axial milling methods may offer some potential toward ‘delamination-free’ drilling of FRP composites. An example of such process strategy is through circular milling by which the tool travels in a helical path through the workpiece material. Recently, several authors have reported the success of circular milling (known as orbital drilling) for hole making of multilayer composite materials that consist of FRP composites and titanium alloys [71, 72].

In another study, Schulze et al. proposed a ‘three-axis’ combined process of circular and spiral millings as well as a ‘five-axis’ wobble milling so that the onset delamination damage in FRP composites can be reduced [64]. The main idea of these process strategies is to direct the process force (thrust force) toward the centre of workpiece
material at entry and exit of the tool during drilling. Unfortunately, the practicality of this method in industry is still of a concern because of its relatively low production rate [64].

2.4.2 Turning and orthogonal cutting of FRP composites

Apart from drilling, machinability studies of FRP composites through turning operation have also received a significant attention among researchers worldwide. This is due to its relatively straightforward cutting mechanisms. It has been reported that Everstine and Rogers were the first, in the 1970s, to develop the theoretical work on cutting FRP composites [73]. They formulated a model to predict machining forces during cutting parallel to fibre (at 0° orientations) using a continuum mechanics approach. However, their reported models were not validated with experimental tests and the authors acknowledged that other modes of cutting behaviours were possible. Since then, many researchers have conducted turning tests to facilitate the fundamental understanding of FRP composites’ machinability. Different effects of machining parameters and material properties on the key machinability output have been reported. Complementary to this, various tool materials and geometries have been tested in order to evaluate the cutting tool performance. The following section reviews some of the results found in the literature.

(A) Tool wear and tool life performance

Sakuma and Seto were the earliest to report on the performance of different tool materials and geometries during machining of FRP composites [74]. They performed turning experiments on both CFRP and GFRP composites at various workpiece fibre angles using a wide range of tool materials. These include carbides (P10, M10, and K10), ceramics and cermets (Titanium carbide, TiC, Titanium Nitride, TiN, and Tantalum Nitride, TaN) tools. However, the authors presented qualitative analyses of wear mechanisms and ranking of tool performance without showing any quantitative evaluations or modelling of the tool life performances.

Turning tests were conducted at relatively mild machining parameters (cutting speed of 4 – 12.5 m/min and feed rate of 0.1 mm/rev) using HSS tool inserts of different cobalt contents by Santhankrishnan et al. [75]. The primary aim was to investigate the wear on
the cutting tools when face turning filament wound glass fibre with epoxy resins. The results of this study showed that the tools experience severe deformation on the nose and cutting edge, even when machining at these low or mild parameters. A cobalt content of 8% was found to be optimum value for tool wear on the edge and flank face. Unfortunately, the authors did not report any quantitative tool life performance from their experiments either.

Kim et al. argued that the prior research studies on turning of CFRP composites have been limited to qualitative investigations of the cutting mechanics and tool wear mechanisms, yet quantitative evaluations on the tool life performance were hardly mentioned [76]. In view of this, they reported experimental results of turning CFRP composites using K10 carbide insert with cutting speeds ranging from 35 to 185 m/min and workpiece fibre wound angles of 0°, 15°, 30°, 45°. Under the flank wear criterion, VB of 0.3 mm, the useful life of the carbide tools were found to be within 5 min of machining time for all of parameters tested. From their Taylor’s tool life equation, the authors showed that the tool life was mostly sensitive to the cutting speed if the fibre angle is high [76]. Surprisingly, they concluded that the tool wear during turning of this composite was not affected much by the cutting speed as it is in metal cutting.

In another study, Sreejith et al. attempted the machining of CFRP composites using TiN-coated carbide and polycrystalline diamond (PCD) tools [77]. This is due to the insufficient performance of HSS and uncoated carbide tools reported in the past. Machining forces, cutting temperature, and tool wear were used to indicate the CFRP machinability. Based on their results, the authors suggested that there is a critical cutting speed, where cutting forces and cutting temperature are the lowest or minimal. As expected, the TiN-coated carbide tools exhibited rapid tool wear compared to that of the PCD tools, even at different machining parameters. Obviously, this is due to the exceptional hardness of PCD tools.

Rahman et al. studied the machinability of CFRP composites under various cutting parameters with three types of cutting tool materials, namely uncoated carbides, ceramic and cubic boron nitride (CBN) [78]. The CFRP specimens had short (discontinuous) and long (continuous) fibre reinforcements. It was reported that the carbide tool
performed better at low cutting speeds, whereas the performance of CBN tool surpassed
the others at high cutting speeds. In addition, ceramic inserts were found to be highly
susceptible to mechanical and thermal shock, which causes chipping of the cutting edge
during machining.

Similar to that of drilling and in view of Kevlar® composites being poor conductors, a
significant improvement in tool life has been exhibited when cutting zone temperature
was reduced through the application of liquid nitrogen [79]. According to the authors,
the magnitude of tool wear was substantially low and may not indicate any failure [79].
A suggestion was made that surface roughness might become the governing criterion to
indicate the rejection of cutting tools during turning of the Kevlar® composites under
cryogenic conditions. Indeed, scanning electron microscopy (SEM) studies have
conspicuously revealed the deterioration of surface roughness as the machining
progresses. Increasing numbers of long exposed fibres on the machined surface can also
be observed.

In a recent study, the influences of machining parameters and workpiece fibre
orientation while turning GFRP composites with solid carbide tools have been reported
by Palanikumar et al. [80, 81]. An experimental design methodology was employed, in
which the operational parameters were set at two different levels. The results from
analysis of variance (ANOVA) showed that the effects of changing machining
parameters (cutting speed and feed rate) on the tool wear were more pronounced
compared to that of the fibre orientation and depth of cut. Although this result is
common to expectation, their reported finding on the effect of fibre orientation on tool
wear is somewhat contrary to the earlier study by Kim et al. [76]. No further
explanations were given to validate or justify their result. Nonetheless, the authors
proposed an empirical equation based on a second order polynomial model to predict
the tool wear under different machining parameters and fibre orientations.

Ceramic cutting tools are believed to provide equivalent performance to PCD and CBN
tools when machining hard materials such as FRP composites. With their cost being
cheaper to that of the PCD and CBN tools, they might be a viable substitute for carbide
tools when machining these composite materials. The performance of Ti[C-N] mixed
alumina insert (code: CC650) and SiC whisker reinforced alumina insert (code: CC670), during turning of GFRP composites have been evaluated in a recent study [82]. However, the reported results were not as substantial as anticipated, Figure 2.15.

![Figure 2.15: Flank wear versus time of alumina cutting tools for machining GFRP composites][82]

Failure of the CC650 insert occurred after 6 min of machining at cutting speed of 250 m/min, feed rate of 0.06 mm/rev and depth of 0.2 mm. The CC670 insert, on the other hand, failed after 9 min of machining under similar parameter [82]. In conclusion, the performance of these cutting inserts is still relatively low in comparison to PCD tools. This is evident in Ref. [83], wherein the authors reported the useful life of PCD tool when turning GFRP composites was 6 – 8 times more compared to that of the carbide tool counterparts with the speeds attainable were much higher too.

(B) Surface quality and machining induced damage

Reliability of the machined components, especially for high performance applications, is critically dependent upon the quality of the surface produced by machining processes [27]. As shown in Table 2.5, surface quality is associated with the alteration of the surface layer and texture induced by machining. The former is known as surface integrity, where changes in mechanical and metallurgical properties of the surface layer occur due to material plastic deformation, phase transformation, and melting of the
machined surface layer [27]. The latter is related to the formation of surface micro-geometry (morphology) due to tool geometry, chip formation mechanisms, machine tool rigidity, and kinematic effects of tool motion relative to the workpiece material [27].

Although measurement of surface micro-geometry for homogenous materials such as metal is often straightforward, it may not be true for non-homogeneous material such as FRP composites. This is due to the irregular and rougher textures presence on the workpiece surface which can cause inconsistent measurement for the surface roughness. Konig et al. asserted that surface texture or roughness of the machined FRP composites is to some extent dependent on the stylus path with respect to the fibre direction [84]. Suggestions were put forward that measurements should be repeated and be along the fibre direction. In addition, the centre line or arithmetic average heights, \( R_a \) should be used instead of the peak to valley height, \( R_t \). In a different study, Ramulu et al. claimed that the \( R_a \) parameter failed to describe the extent of surface variation observed by visual analysis [27]. The authors reported the suitability of surface roughness parameters after trimming graphite epoxy composites with PCD tools was explored. Similar to Konig et al. [84], they also concluded that the roughness parameters and profiles are highly dependent on the fibre orientation and direction of measurement.

It is well known that as far as the influence of machining parameters on surface roughness is concerned, a theoretical expression (generally used in metal cutting) in the form of:

\[
R_a = \frac{f^2}{18\sqrt{3R}}
\]

can be used to predict surface roughness, \( R_a \) based on a given feed rate, \( f \) and tool nose radius, \( R \) [85]. Experimental results during turning of FRP composites (as reported in the past research studies) exhibited a similar relationship shown above [86-97]. Some of recently reported studies have parametrically shown, through the DOE method, that the effects of cutting speed were trivial. Although it is well known that the degree of tool wear also influences the surface quality, the aspect of tool wear was not considered in some of those studies, which is somewhat odd with respect to any machinability study.
With regard to tool geometries on cutting performance, Lee et al. reported the results of experiments which investigate the optimal cutting tool geometries during machining of GFRP composites [98]. The geometries of the tool used were the R-type tool of 0.5 mm nose radius and the S-type tool with 1.5 mm straight edge with tool materials ranging from single crystal diamond, PCD, and CBN. In order to meet an acceptable surface finish with low cutting force, single crystal diamond tool has been recommended. It was observed that a tool with a straight edge is better than a tool with a round nose in improving the surface finish. The authors also highlighted that unlike in metal cutting where the formation of built-up edge often results in better surface finish, this phenomenon may not be true for FRP composites machining due to its inherent chip forming mechanism [98].

Some fundamental insights into various aspects of machining induced damage were realised through the studies of chip formation mechanisms by several researchers in the past. Koplev et al. contributed the first chip formation studies through orthogonal cutting of CFRP composites in the 0° and 90° fibre orientations [9]. The authors asserted that the substantial difference between machining of FRP composites and metal was that the chips were not subjected to a large plastic deformation during cutting. As a result, the cutting process was observed to consist of a series of fibres and matrix fractures due to loading of the tool tip on workpiece material. Using a ‘quick-stop’ device, the authors examined and explained crack propagation mechanisms in the FRP composites as the tool machined parallel and perpendicular to the fibres, Figure 2.16.

Figure 2.16: Cross-section of specimens showing mechanisms of chip formation leading to machining induced damage for (a) cutting parallel and (b) perpendicular to fibre [9]
It appears that the limitation of Koplev’s work is in the fact that only two fibre orientations (0° and 90°) were taken into consideration. In view of this, Takeyama and Ijima [99] included other workpiece fibre angles ranging from 0°, 30°, 45°, 60° to 90° in their chip formation studies of GFRP composites. Quite surprisingly and incongruent to the study by Koplev et al., the authors reported that the chip formations in most of the fibre angled specimens were similar to that of metallic materials [99].

Wang et al. proposed and explained the mechanics of chip formation during orthogonal machining of uni-directional CFRP composites with various tool rake angles and workpiece fibre orientations [100-102]. It was highlighted that the cutting mechanisms are to a greater extent dependent on fibre angle, but less on the rake angle. Various fibre failures modes, which include Mode I, delamination; Mode II, fibre buckling, Mode III-IV fibre cutting (continuous or discontinuous chip), and Mode V, macro-fracture; have been demonstrated. It is to be noted that detailed discussion on these fibre failure modes can be found in Ref [3, 101].

(C) Other recent advances
Experimental approaches for physical cutting mechanisms of FRP composites are often time consuming and expensive. Because of these reasons, many have resorted to numerical simulation such as Finite Element Method (FEM) to predict the macroscopic and microscopic responses of FRP composites machining. In conjunction with composite material failure criteria such as Tsai Hill, Hashin’s theory, Maximum stress, and Hoffman failure criteria; the chip formation processes, machining forces and force induced-damage modes such as matrix cracking, fibre–matrix debonding and fibre breaking have been successfully modelled and predicted in past research studies [103-109]. The developed models and presented simulations have included all possible macro and micro conditions of the composite materials, which provides fundamental understandings into FRP composites cutting mechanics. However, numerical results from FEM are usually limited to the cutting parameters (speed, depth) that are far below than those typically employed in practice.

An innovative simulation technique for chip formation mechanism during orthogonal cutting of uni-directional CFRP composites through a Discrete Element Method (DEM)
has been introduced recently by Illiescu et al. [110]. According to the authors, DEM model was initiated for geotechnical applications. Several other disciplines such as in tribological and abrasion process later have found the benefits of using this technique. In their study, the authors claimed that the qualitative validations of the DEM chip formation mechanisms were made possible by comparing the experimental chip formation captured using a high-speed video camera. The authors also asserted that the DEM tool was able to predict the force generated during cutting operation. In spite of this, it is imperative to highlight that the magnitude of machining forces from DEM simulation has significantly been overestimated or underestimated for most of the cases considered therein.

2.4.3 Milling of FRP composites

Milling is the family of machining processes in which the unwanted material is removed by a rotating multiple tooth cutter. Each tooth removes a small amount of material from the advancing workpiece during each spindle revolution. Unlike turning operations, the tool engagement on workpiece material is intermittent and discontinuous chips are usually formed, Figure 2.17.

![Figure 2.17: End milling of rectangular workpiece material](image)

On the basis of its efficient and effective material removing process, this process is typically used in metal cutting, particularly for machining of flat, contoured, and helical
surfaces of the workpiece materials. In the case of FRP composites, milling is widely employed in industries for various purposes. This includes edge trimming, grooving, and removing of excess material so that different functional shapes and dimensional tolerances can be obtained. As the scientific understanding of FRP composites cutting mechanics for drilling, turning, and orthogonal processes have mature, the focus must now switch to complex process such as milling. This section of the chapter discusses the earliest and recent reported studies on milling FRP composites. A review table, Table 2.6, presented at the end of this section offers the readers a quick comparison and limitation of the published literature with respect to this machining process.

Earliest literature regarding milling of FRP composites was reported by Hocheng and Puw [111]. In these studies, they investigated the cutting of uni-directional CFRP composites using a single square carbide insert. The experiments were conducted at cutting speeds ranging from 30 – 190 m/min, table feed speed of 50 to 150 mm/min and a constant depth of 1 mm. Based on the articles, the authors asserted that workpiece fibre orientation has a significant effect on the formation of burrs and surface roughness. The cut was clean showing no fibre roots on the machined surface when the tool was fed along the fibre orientation (0° fibre orientation). Many uncut fibres were, unfavourably, observed when machining at 90° and 45° fibre angle, as the cutting tool is liable to slip over the fibres during cutting [111].

With regard to tool wear or tool life, abrasion was found to be the dominant tool wear mechanism. The useful life of the tool (using tool flank wear criterion of 0.6 mm) was determined to be approximately 16 and 18 min when machining along the fibres and across the fibre orientation respectively. However, the reported results of this study were purely experimental without analytical or empirical modelling being proposed. Little work, other to that presented by Hocheng et al. and Rahman et al. [111, 112], have discussed the evaluation of tool wear during milling of FRP composites. Until recently, the published studies on milling of these composite materials have focused largely on surface roughness and delamination damage [113-116], with the aspect of tool performance is not fully addressed.
As far as modelling of milling FRP composites is concerned, Kalla et al. [117] have recently developed a committee neural network model in predicting the machining forces during the machining process. In their study, a mechanistic cutting force model which was based on the committee neural network has been modelled for CFRP composites during helical milling. The proposed model covers uni-directional and multidirectional composites with fibre angles of 60°/0°/120°. Nonetheless, this work was limited to constant cutting speed and table feed speed of 2,000 RPM and 406 mm/min respectively. The accuracy of the proposed prediction model was reported to be fairly reasonable for the helical milling of uni-directional composites. In view of this, the authors believed that the variations may arise due to mismatches in specific cutting energy coefficients and inaccuracy of assumptions made, in which the coefficients were independent of the tool inclination angle [117].

Another force mechanistic model during milling of CFRP composites has been proposed by Karpat et al. [118]. Cutting force coefficients in radial and tangential directions are calculated as a function of fibre cutting angle. The relationship was represented with simple sine functions and the model was shown to be capable of predicting cutting forces during milling of uni-directional and multidirectional CFRP laminates. Although the authors asserted that delamination is known to be closely related to machining force and tool wear, the effects of tool wear were not disclosed in their published results.

A recent study has reported the occurrence and propagation of top layer delamination during a slot milling of CFRP tapes [119]. The tests were conducted using double straight edged PCD tool at a constant speed of 800 m/min and feed of 0.06 mm. The authors demonstrated the different delamination mechanisms associated with various tool edge radius and workpiece fibre angles. However, it was claimed that regardless of the speed, tool material, and its sharpness, there is a critical fibre cutting angle in which delamination and fibre overhangs still occur.

As discussed in the earlier section, chip formation mechanisms often provide useful information with regard to machining induced damage of FRP composites. It is also necessary to note that phenomena related to macro-machining may not be truly applied
for the micro-machining cases. Considering these, Calzada et al. proposed a model for failure mechanism of fibre as a function its orientation while micro-milling of CFRP composites. The carbon fibres oriented at 90° and 45° degrees to the direction of motion of the cutting tool were exhibited to fail predominantly by crushing/compression. Whereas, buckling and bending-dominated tensile failures, were observed for the 0° and 135° orientations, respectively [120]. The authors utilised the chip morphologies and delamination patterns observed from the milling tests to support the suggested fibre failure modes.
Table 2.6: Summaries of reported literature on milling of FRP composites

<table>
<thead>
<tr>
<th>Reference</th>
<th>Tool</th>
<th>Tool Material</th>
<th>Fibre Type</th>
<th>Reinforcement</th>
<th>Fibre Volume Fraction</th>
<th>Matrix</th>
<th>Machining Parameters</th>
<th>Machinability Performance</th>
<th>Tool Wear (mm) or Tool Life (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[112]</td>
<td>K20</td>
<td>Carbon fibre</td>
<td>Short fibres</td>
<td>30%</td>
<td>PEEK</td>
<td>100, 230</td>
<td>125, 250</td>
<td>0.5, 2</td>
<td>0.4 – 0.6</td>
</tr>
<tr>
<td>[113, 114]</td>
<td>K10</td>
<td>Glass fibre</td>
<td>Not mentioned</td>
<td>65%</td>
<td>PE</td>
<td>47.1, 78.5, 110</td>
<td>120, 400, 840</td>
<td>2</td>
<td>1.38 – 2.04</td>
</tr>
<tr>
<td>[115]</td>
<td>K10</td>
<td>Carbon fibre</td>
<td>Woven (0/90)</td>
<td>55%</td>
<td>Epoxy</td>
<td>28, 38, 47</td>
<td>200, 410, 860</td>
<td>2</td>
<td>1.16 – 2.79</td>
</tr>
<tr>
<td>[121, 122]</td>
<td>WC</td>
<td>Carbon fibre</td>
<td>Uni- &amp; Multi-directional</td>
<td>60%</td>
<td>Epoxy</td>
<td>23</td>
<td>217</td>
<td>0.6, 0.9, 1.8</td>
<td>NS</td>
</tr>
<tr>
<td>[28]</td>
<td>Solid carbide</td>
<td>Solid carbide burr tool</td>
<td>Carbon fibre</td>
<td>Woven (45/135/0/90)</td>
<td>NS</td>
<td>NS</td>
<td>100 – 300</td>
<td>2.54, 5.08, 10.16</td>
<td>NS</td>
</tr>
<tr>
<td>[123]</td>
<td>Diamond</td>
<td>Carbon fibre</td>
<td>Woven (±45)</td>
<td>50%</td>
<td>NS</td>
<td>60</td>
<td>1270, 2540</td>
<td>1</td>
<td>3 – 8</td>
</tr>
<tr>
<td>[124]</td>
<td>TiN WC</td>
<td>Carbon fibre</td>
<td>Woven (90, ±45)</td>
<td>63%</td>
<td>Epoxy</td>
<td>18, 25, 35</td>
<td>0.076, 0.127, 0.178</td>
<td>1</td>
<td>1.4 – 2.1</td>
</tr>
<tr>
<td>[116]</td>
<td>HSS</td>
<td>Glass fibre</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>500–1,600 (RPM)</td>
<td>200, 350, 500</td>
<td>1, 2, 3</td>
<td>6.07 – 6.87</td>
</tr>
<tr>
<td>[125]</td>
<td>HSS, WC, WC TiAlN</td>
<td>Carbon fibre</td>
<td>Woven (0,45,90,-90)</td>
<td>35 – 60%</td>
<td>NS</td>
<td>82.4</td>
<td>260</td>
<td>2 – 3</td>
<td>NS</td>
</tr>
</tbody>
</table>

2.5 Cutting Tool for Milling FRP Composites

2.5.1 Tool materials

In parallel with the development of new engineering materials for various product requirements, similar progress in the range and performance of cutting tool material can be seen in the past few centuries, Figure 2.18. It is well known that PCD tools are by far the most superior and extremely beneficial for high-speed machining due to their excellent thermal conductivity and high hardness (wear resistance). In spite of this, the range of operations in which they are used need to be carefully optimised because of their deficiency to resist shock (low toughness) [19], e.g. they are susceptible to fracture. Notably, PCD tools only found distinctive applications in machining ‘difficult to cut material’ under extreme cutting conditions. On the basis of their cost, it has been reported that PCD tools current market share is relatively low in comparison to the conventional tool materials such as carbide tools [126].

![Figure 2.18: Development of cutting tool materials and their achievable cutting speed in the various machining operations [127]](image)

The cemented carbide tools can be said to be universally applied and a first choice cutting tool material in most industrial cutting applications, whether in drilling, turning or milling operations [127]. Based on the published literature, researchers have come to the agreement that this tool material can be used, with a reasonable success, to machine the highly abrasive FRP composites. One of the reasons for the success of carbide tools is the useful compromise between toughness and hardness properties, as illustrated in Figure 2.19 [127]. This tool material consists of hard carbide particles, mainly tungsten carbides (WC) bonded with metallic binder, cobalt (Co), as depicted in Figure 2.20, manufactured through powder metallurgy processes.
It is to be noted that the proportion of WC particles can range from 70 to 97 wt% with their grain size typically around 0.4 to 10 microns. Depending on the application group (long chip or short chip materials), the WC tools are further classified into three grade groups of P, M and K. Along with these designations, a numbering system is given to indicate the suitability of the grade for a variety of applications from light finishing (01) to heavy roughing (50) machining processes. Such examples of the grade systems are the K01, K10, K20 or K30 grades. On the other hand, despite some benefits in metal machining, similar results have not been able to be delivered by the coated carbides during machining of the FRP composites, as presented in the earlier section. The uncoated tungsten carbide continues to be the choice among researchers and practitioners for FRP composites machining. Widely and readily available, this tool can accommodate the broadest range of cutting geometries and parameters [128]. The low price of carbide tools also allows the machine shop to consume many units of them before approaching the cost of a PCD tool [128].
2.5.2 Cutting tool geometry

In conjunction with the cutting tool material, selection of proper cutting tool geometry is of extreme and equal importance during end milling of FRP composites. As in drilling operations, a variety of cutting tool geometries is available for milling, as depicted in Figure 2.21. The design of end mill cutter geometry stems from diverse types of fibres and architecture of FRP composites utilised for various industrial applications [3]. Referring to the tooling system for wood machining and types of milling operations, a list of cutting tool geometries suitable for these composites have been proposed. This includes straight flute router, single and double helix cutter, and interlocking burr tool, as outlined in [3]. Straight flute route may be the simplest geometry and can be effectively use for trimming of composite panels, but this tool tends to clog due to its poor chip removal [3].

![Figure 2.21: Cutting tool geometry for milling FRP composites (a) straight flute router, (b-d) single helix and (e-f) multiple helix tool and burr tool [3]](image)

On the other hand, the diamond interlocked solid carbide burr tools, which are specially design for FRP composites, Figure 2.21 (e-f), often use during high speed routing of the composite materials. However, due to a number of teeth being simultaneously engaged during cutting, the chip formation is not well defined [28]. As a consequence, the growth of tool wear will not be gradual (non-uniform) which makes it difficult to estimate the tool regrinding or re-sharpening time prior to reaching the tool failure criterion. The single helix or double helix tools may, therefore, provide the advantages of monitoring the progression of the tool wear directly and easily. It is to note that all
cutting tool design for milling of FRP composites may exhibits clogging problems during machining owing to the small diameter and improper selection of cutting parameters [3]. Continuous blowing of compressed air into the cutting zone along with an effective dust extraction system during machining can help alleviate this problem.

### 2.6 Dry Machining of FRP Composites

The use of coolants or lubricants during machining of metals is typically to aid the cutting action and assist of swarf removal [19]. However, due to environmental awareness and health issues, efforts have been made to reduce or eliminate the consumption of cutting fluid or coolant during machining processes. Observations on the past research studies on machining of FRP composites have revealed that most of them were performed under dry conditions. Apparently, results of past reported experiment have not highlighted of any benefits in using coolants for FRP composites machining either [112]. Except for the work by Bhattacharyya et al. [10, 79] during cryogenic drilling and turning of Kevlar® composites, limited information is available regarding superior results (either tool life or machining quality) with the use of coolant or lubricants. Dry and high speed machining of FRP composites have been known to produce a significant amount of dust particles (fractured fibres and polymer resins) in the size of 8 – 20 μm [129]. This brings about a health hazard to the machine operator due to inhalation of the dust particles. These dust particles are also harmful to the machine tool when they become airborne and penetrate into machine slide-ways, which may abrade some of the critical machine components. As a result, the use of an effective dust extraction system is highly recommended in evacuating the generated chips during dry machining operation. This attenuates any chip interference that could lead to a local heat accumulation in the cutting zone.

### 2.7 Tool Condition Monitoring during Machining

It is well understood that the direct contact between cutting tool, workpiece material, and the chips during machining imposes stresses on the tool. As a result, changes to the
geometry, volume loss, and sharpness of the cutting tool, can occur either gradually or abruptly. These changes, which are known as tool wear, typically take place at rates dependent upon machining parameters, workpiece material as well as the cutting tool material or geometry. As discussed earlier, abrasive wear on the flank face of the cutting tool has been the dominant wear mechanism that influences tool sharpness during machining of FRP composites. On the basis of this, reduction of sharpness puts constraints on the improvement in part dimensional accuracy and surface qualities of the FRP composites’ product. Often, in-service or mechanical performance of poorly machined FRP composites degrades and in worst circumstances, makes them rejected prior to the end applications of the composite materials. Similar to that of metallic materials, it is vital to be able to monitor the condition of the cutting tool, prior to the end of its life during machining so as to avoid such issues.

There exists a significant body of literature pertaining to tool condition monitoring for metal cutting processes reported in the past few decades. The concept of tool condition monitoring has evolved in the early 1990s. In general, condition of the cutting tool can be determined through two possible methods, namely direct and indirect methods. Broadly speaking, Li Dan and Matthew [130] define them to be as:

- direct, where the actual tool wear is measured in situ;
- indirect, where a parameter correlated with tool wear is measured.

Table 2.7 summarises various approaches of tool wear measurement and conditioning under these two methods. Direct inspection using optical devices has been extensively and effectively employed in the past in order to study the extent of tool wear as well as to understand its mechanisms. The optical measurement of tool flank wear has also been proven to be useful in estimating the tool life by developing the classical Taylor’s tool life equation. However, this requires interruptions of the cutting operations due to the need to remove the tool from its holder for the optical microscopy. This consequently demotes machining productivity due to unscheduled downtime of the cutting operation.

An indirect approach that involve the measurements of machining signals, which can be correlated to the tool wear, offers a more practical solution for industrial application.
Literature Review

Thanks to the availability and on-going advancement of various sensors for machining tests in recent years, reliable and accurate monitoring of tool condition can be realised. Nonetheless, machining operation is known to produce harsh environment or conditions. In view of this, Dimla summarised that any machining processes can be classified as having one or more of the following characteristics [131]:

- complex to chaotic behaviour due to in-homogeneities in the workpiece material;
- sensitivity of the process parameters to cutting parameters; and
- nonlinear relationship of the process parameters to tool wear.

The aforesaid stochastic phenomenon makes it a challenge to achieve highly accurate and reliable tool condition or prediction models. In fact, on the basis of complexity in the tool wear growth, developing an indirect monitoring of tool wear based on analytical or numerical models would rather be impractical if not impossible. As a result, empirical based model evaluated from experimental data or machining signals is viable enough to draw scientific conclusions about the tool condition. Such signals can come from various sources, Table 2.7, although machining forces have predominantly been used in past research studies. This is evident in the summary of selected literature (taken from a broad spectrum of research articles) related to the tool condition monitoring, Table 2.8.

Referring to the summary in given Table 2.8, machining forces are considered to be the most informative indirect tool wear monitoring signals. They can be directly correlated to the sharpness of the cutting edges (tool wear), chip geometry, and machining parameters. Frictions between cutting tool and the workpiece material produce variations of machining forces, which can easily indicate the tool wear conditions. Conversely, severe plastic deformation, tool-material contact and collision, chip breakage, and tool fracture, during the cutting process can promote the release of strain energy. This released energy, commonly referred to as acoustic emission (AE) or strain wave, is a result of disturbance in materials’ microscopic structure.
Table 2.7: Direct and indirect tool wear measurement and condition [130, 132]

<table>
<thead>
<tr>
<th>Methods</th>
<th>Procedure</th>
<th>Measurement</th>
<th>Sensor/Transducer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>Optical</td>
<td>Shape or position of cutting edge</td>
<td>Optical microscope; CCD camera</td>
</tr>
<tr>
<td>(In situ)</td>
<td>Volumetric loss</td>
<td>Measurement of size and concentration of wear particles</td>
<td>Spectrophotometer; scintillate</td>
</tr>
<tr>
<td></td>
<td>Tool/workpiece distance</td>
<td>Change of distance between tool and workpiece material</td>
<td>Micrometer; pneumatic gauge; displacement transducer</td>
</tr>
<tr>
<td>Indirect</td>
<td>Machining forces</td>
<td>Development of machining forces with respect to time</td>
<td>Dynamometer; strain gauges</td>
</tr>
<tr>
<td>(Phenomenon related to tool wear)</td>
<td>Electrical current, power, or energy</td>
<td>Power or current consumption of spindle and feed motor</td>
<td>Ampere meter; Voltmeter</td>
</tr>
<tr>
<td></td>
<td>Vibration and acoustic emission</td>
<td>Vibration measurement of tool and airborne sound</td>
<td>Accelerometers; AE transducer, Microphone</td>
</tr>
<tr>
<td></td>
<td>Cutting temperature</td>
<td>Variation of cutting temperature, reflectance on chip surface or colour</td>
<td>Thermocouple; Pyrometers</td>
</tr>
</tbody>
</table>

It is evident that several studies have reported the success of using AE for tool condition monitoring, Table 2.8. Yet, it is imperative to be noted that AE sensors are highly sensitive to any noise generated from the external environment. Hence, application of AE sensors as a tool wear indicator is only deemed to be suitable as an additional sensing device in support to the main sensor or device.

It is also well known that the friction between cutting tool and the workpiece material often generates a significant amount of heat. The resultant temperature around cutting tool edges has a direct influence on the rate and mode of cutting tool wear [133]. Nonetheless, past attempts to measure cutting edge temperature have been challenging and difficult. This is due to the lack of direct access to the cutting zone, particularly at the tool tip, which makes it insufficient for tool condition monitoring.

Presently, among many research endeavours on tool condition monitoring, one can find limited numbers of published results for composite materials. The only such study was reported by Lin et al. during turning of aluminium silicon carbide MMC(s) [134]. Effort
must be undertaken to extend the concept of tool condition monitoring from metal cutting process into composite machining, especially the FRP composites, for any industrial useful applications. Notably, a timely decision on tool condition prior to the end of its useful life is crucial in order to reduce any effects of the worn tool on the machined surface. In spite of this, chaotic behaviour of machining response seems to impede the progress of developing a reliable tool wear predictive model for any practical use during machining of these materials due to the non-homogenous nature of the FRP composites.
### Table 2.8: Overview of selected past reported research on tool condition monitoring using various sensors for different workpiece material

<table>
<thead>
<tr>
<th>Authors</th>
<th>Material type</th>
<th><strong>Machining Processes</strong></th>
<th><strong>Types of sensors</strong></th>
<th><strong>Data processing and analysis for tool condition monitoring</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Drilling</td>
<td>Turning</td>
<td>Milling</td>
</tr>
<tr>
<td>Ravindra et al. [135]</td>
<td>Cast Iron</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Patra et al. [137]</td>
<td>Mild steel</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emel and Kannatey [138]</td>
<td>Different material hardness</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jemielniak &amp; Arrazola [139]</td>
<td>Tool steel</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lin et al. [134]</td>
<td>Aluminium SiC MMC(s)</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lin &amp; Ting [140]</td>
<td>Copper alloy</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sanjay et al. [141]</td>
<td>Mild steel</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lin &amp; Lin [142]</td>
<td>6061 Aluminium Alloy</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:** FD - Force dynamometer; AE - acoustic emission; Others – accelerometers, thermocouple.
Cont’ Table 2.8: Overview of selected past reported research on tool condition monitoring using various sensors for different workpiece material

<table>
<thead>
<tr>
<th>Authors</th>
<th>Material type</th>
<th>Machining Processes</th>
<th>Types of sensors**</th>
<th>Data processing and analysis for tool condition monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feng et al. [143]</td>
<td>MgO Zirconia</td>
<td>Drilling</td>
<td>✓</td>
<td>Grinding process but data analyses method was not specified</td>
</tr>
<tr>
<td>Malekian et al. [144]</td>
<td>Not mentioned</td>
<td>Turning</td>
<td>✓</td>
<td>Adaptive network based fuzzy inference system</td>
</tr>
<tr>
<td>Kuo &amp; Cohen [145]</td>
<td>Chromium-Vanadium alloy</td>
<td>Milling</td>
<td>✓</td>
<td>Fuzzy modelling and multilayer feed-forward neural network</td>
</tr>
<tr>
<td>Chen &amp; Li [146]</td>
<td>Inconel 718</td>
<td>Others</td>
<td>✓</td>
<td>Adaptive controller</td>
</tr>
<tr>
<td>Saglam &amp; Unuvar [147]</td>
<td>AISI 1040</td>
<td></td>
<td>✓</td>
<td>Multilayer feed-forward neural network</td>
</tr>
<tr>
<td>Liu &amp; Altintas [148]</td>
<td>P20 steel</td>
<td></td>
<td>✓</td>
<td>Multilayer feed-forward neural network</td>
</tr>
<tr>
<td>Das et al. [149]</td>
<td>C20 carbon steel</td>
<td></td>
<td>✓</td>
<td>Back propagation neural network</td>
</tr>
<tr>
<td>Kakade et al. [150]</td>
<td>Mild steel</td>
<td></td>
<td>✓</td>
<td>Correlation between tool wear and ringdown counts of AE signals</td>
</tr>
<tr>
<td>Raman et al. [151]</td>
<td>Not mentioned</td>
<td></td>
<td>✓</td>
<td>Mathematical modelling using remote thermocouple sensor</td>
</tr>
</tbody>
</table>

** Notes: FD - Force dynamometer; AE - acoustic emission; Others – accelerometers, thermocouple.
2.8 Soft Computing Modelling of Machinability Performance

Due to the complexity of machining processes and variability in material properties, analytical or physical models are often unable or difficult to describe the mechanics of machining processes. The underlying nonlinear relationships between machining parameters and output measures make it a challenge to derive analytical or mathematical models accurately. In view of that, empirical models evaluated from experimental data have been extensively employed in the past to model machining processes. A commonly used statistical technique (known as regression analysis), has been known to provide a decent prediction of machining performance based on a prior assumption of either a linear, quadratic, higher order polynomial or exponential function (with regard to the constitutive relationship(s) of experimental parameters). Recently, soft computing modelling has emerged as an alternative method to complement the statistical technique for modelling of machining processes. Indeed, successful implementations of soft computing approaches for modelling of metal machining have been summarised in several review reports [152-155]. Soft computing, as the name suggests, refers to a collection of computational techniques developed from computer science research, with the major aims of being able to model and analyse complex, nonlinear, and imprecise phenomena that may exist in the process variables. Soft computing modelling is usually robust and capable of yielding complete, accurate, and reliable solutions. Such examples of soft computing modelling frequently employed in machining research include artificial neural network (ANN), fuzzy logic modelling, and genetic algorithms (GA), Figure 2.22.

Table 2.9 at the end of this section, summarises the published literature pertaining to the applications of soft computing techniques in modelling the FRP composites machining. It appears that both ANN and fuzzy logic modelling have been employed to predict a variety of FRP composites machinability outputs such as delamination damage, surface roughness, thrust/machining forces, and tool wear. Despite this, ANN has attracted more attention among researchers to model the constitutive relationship of machining process due to its superiority in learning the process variables. The capability of ANN to perform nonlinear and imprecise computations is based on the emulation of biological neural networks of a human brain.
Principally, a biological neural network within a human brain runs according to the training or learning procedures of inter-connected information-processing neurons. Figure 2.23 depicts a single network which carries information and transfers it to other neurons in a chain of networks through signals emitted by the dendrites so as to promote the learning process of the synapses. ANN imitates these functions and their unique process of learning by means of inter-connected elements operating in parallel, in order to compute or determine a function, $f$ that matches a given set of examples or observations, $f : X \rightarrow Y$.

ANNs are usually classified based on their topologies (architectures) and the method of training. The most common neural network architectures are; (1) the feedforward,
the feedback, and (3) the self-organizing neural networks [153]. Figure 2.24 exhibits an example of a feedforward neural network architecture that consists of three layers. Noticeably, each layer, which has full interconnection to the next layer, contains a number of neurons as depicted by the circles. The first layer of the network is known as the input layer, whose neurons take on the values corresponding to different variables representing the input pattern. The second layer is known as a hidden layer because its outputs are used internally and not calculated as the final output of the network. Finally, values of the neurons from the output layer constitute the overall response of the neural network to the input patterns presented at the first layer.

![Figure 2.24: A feedforward neural network](image)

Feedforward mechanism of this network facilitates the training/learning process of the neurons to fit the targeted output layer. In fact, throughout the learning process, a cost function, $C$, is often employed to measure how far a neural network solution is scattered from the optimal case. In view of that, the learning algorithms of the neural network are used in determining the smallest possible cost function within the solution space. A typical used cost function is the mean square error (MSE) of the network's output and the target value over all data pair examples.

As reported in various peer-reviewed research articles, the feedforward neural network is the widely utilised ANN architecture in modelling the machining response. These include the multi-layer perceptron (MLP) neural network and radial basis function (RBF) neural network. The differences between them are merely in terms of the number

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53
of hidden layer and activation functions’ type. The former has more than two hidden layers, whereas, the latter has a single hidden layer. In RBF, Gaussian activation function is often used, as opposed to the hyperbolic tangent and sigmoid functions for the MLP neural network. Irrespective of the neural network type; the numbers of neurons in the hidden layer, the weight parameters, and activation functions have to be chosen judiciously in effort to avoid chaotic results (prediction) in the output layer [153]. In general, the tasks of which ANNs are applied fall within the following broad categories:

- Function approximation, or regression analysis, including time series prediction, and modelling;
- Classification, including pattern and sequence recognition, novelty detection, and sequential decision making;
- Data processing, including filtering, clustering, and blind signal separation.

Similar to that of ANN, fuzzy logic models also constitute one of the modelling tools in soft computing [156]. Having said this, the theory of fuzzy logic was initially proposed in the 1965 by Lotfi Zadeh as a tool to deal with uncertainty in a system. Following that idea, Assilian and Mamdani reported the earliest implementation of fuzzy logic rules for the controller of a steam generator [156]. Since then, many researchers have demonstrated the successful implementation of fuzzy logic models in various forms of products and systems. In conjunction with advancement in computing capabilities, fuzzy logic controllers have been applied in various aspects of research work which include, pattern recognition (classification), signal processing, and robotics control. Fuzzy logic has recently becoming attractive for approximation of multivariate and nonlinear process functions. Indeed, Kecman asserted that the unique characteristics of fuzzy logic enable it to model unknown mathematical relationship or when mathematical relationships are impossible to be obtained accurately [156].

Typically, fuzzy logic represents a system or a model by employing human reasoning or human structured knowledge in the form of rules, as opposed to using complex mathematical models or equations. Most often, neural network and fuzzy logic are used as a stand-alone computation tool. However, due to individual shortcomings, a
combination of both would yield superior results. In fact, successful applications of hybrid modelling have been evidently demonstrated in a few research reports of material and machinability modelling [157-159]. This modelling method is known as adaptive network-based fuzzy inference system or simply, ANFIS. Details of this hybrid neural network and fuzzy logic model implemented during the course of this study are further elaborated in a later chapter, Chapter 6.
Table 2.9: Summary of artificial neural network and fuzzy logic modelling employed during machining of FRP composites as reported in past research

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Machining Process</th>
<th>Input Parameters</th>
<th>Output Parameters</th>
<th>Type of neural network or fuzzy analyses</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Speed</td>
<td>Feed rate</td>
<td>Depth of cut</td>
<td>Cutting Force</td>
</tr>
<tr>
<td>GFRP</td>
<td>Milling</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>CFRP</td>
<td>Milling</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>GFRP</td>
<td>Turning</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>GFRP</td>
<td>Turning</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>GFRP</td>
<td>Turning</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>GFRP</td>
<td>Turning</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Note:
BP/MLP – Backpropagation and multi-layer perceptron, RBF – Radial basis function, FL – Fuzzy logic, Other – Committee neural network, Ra – Surface roughness, Fc – Cutting/Thrust force, P – Pressure, Ps – Specific cutting pressure, Ct – Chip thickness, TW – Tool wear
X*: Type of insert, workpiece material
Cont: Table 2.9: Summary of artificial neural network and fuzzy logic modelling employed during machining of FRP composites as reported in past research

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Machining Process</th>
<th>Input Parameters</th>
<th>Output Parameters</th>
<th>Type of neural network or fuzzy analyses</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFRP</td>
<td>Turning</td>
<td>Speed Feed rate</td>
<td>Tool Geometry</td>
<td>Ra, TW</td>
<td>X</td>
</tr>
<tr>
<td>CFRP</td>
<td>Drilling</td>
<td>X</td>
<td>Tool Geometry</td>
<td>Ra, Fd, HC</td>
<td>X</td>
</tr>
<tr>
<td>GFRP</td>
<td>Drilling</td>
<td>X</td>
<td>Tool Geometry</td>
<td>RS</td>
<td>X</td>
</tr>
<tr>
<td>GFRP</td>
<td>Drilling</td>
<td>X</td>
<td>Tool Geometry</td>
<td>Fd, Fc</td>
<td>X</td>
</tr>
<tr>
<td>CFRP</td>
<td>Drilling</td>
<td>X</td>
<td>Tool Geometry</td>
<td>Fc</td>
<td>X</td>
</tr>
</tbody>
</table>

Note:
- BP/MLP – Backpropagation and multi-layer perceptron
- RBF – radial basis function
- FL – fuzzy logic
- Other – committee neural network
- Ra – surface roughness
- Fc – Thrust force
- Fd – Delamination damage
- HC – Hole circularity
- RS – Hole residual strength
- X** – Fibre orientation, machining time
Chapter 3 Experimental Procedure

This chapter discusses the experimental set-up designed for the end milling machinability tests of glass fibre-reinforced polymer (GFRP) composites. It starts with descriptions on the GFRP test panels fabrication and their characterisation methods. This is followed by detail explanations on various equipment and instruments used for measuring the machinability responses.

3.1 Fabrication of GFRP Composite Specimens

3.1.1 Selection of fibre reinforcement and matrix material

The selected fibre reinforcement was the uni-directional E-glass fibre (EU450-1270), Figure 3.1, supplied by SP High Modulus (NZ). E-glass fibre is favourable as it provides the key structural properties of a composite material. These include high specific-stiffness and strength, corrosion as well as fatigue resistance. It also has excellent impact strength when combined with the softer matrix material. Apart from the performance criteria, this reinforcement is of interest because the fibre orientations can be deliberately aligned at any desired orientation for machining tests. The E-glass fibre was also chosen as it is less expensive compared to other types of fibre reinforcements, e.g. carbon fibres and Kevlar®.

The polymer matrix used for fabrication of the composite material was the R300 thermoset epoxy resin with the R310 hardener, both supplied by Nuplex FGI Ltd. Epoxy is chosen as it is a versatile resin system that allows a broad range of FRP composites’ properties and processing capabilities. It is also well known that epoxy
Experimental Procedure

resin exhibits low shrinkage, excellent adhesion, and impregnation characteristics to a
variety of substrate materials especially the E-glass fibres [169]. The Nuplex resin
systems have been selected because of their suitability for resin infusion and being
readily available on the shelf. Brief specifications of the E-glass fibre, epoxy resin and
the hardener used are listed in Table 3.1.

![Figure 3.1: Close-ups of the E-glass reinforcement](image)

Table 3.1: Specifications of fibre reinforcement and thermosetting resin

<table>
<thead>
<tr>
<th>Specifications</th>
<th>E-Glass</th>
<th>Epoxy resin</th>
<th>Hardener</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>2560</td>
<td>1200</td>
<td>-</td>
</tr>
<tr>
<td>Areal density (g/m²)</td>
<td>480</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Product code</td>
<td>EU450-1270</td>
<td>R300</td>
<td>R310</td>
</tr>
</tbody>
</table>

3.1.2 Manufacturing of test panels

Vacuum-assisted resin transfer moulding, also known as resin infusion, was adopted to
fabricate the composite laminates for the machining experiments. This process offers
several advantages over conventional composite fabrication methods such as wet hand
lay-up, as highlighted in Chapter 2. Higher quality of the composite laminates, e.g. high
volume fraction with minimal void contents, can be produced using the VARTM
process [6]. This process also provides a safe and clean fabrication environment
compared to that of the traditional wet hand lay-up.
As elaborated in Chapter 2, the basis of VARTM is that the liquid epoxy resin is drawn into the mould cavity under vacuum pressure to impregnate the dry fibre reinforcements. The porosity of the cured composite laminates can be reduced significantly through the application of the vacuum pressure into the mould cavity. During the fabrication, a flat glass panel of 1200 mm x 800 mm (placed on a steel frame table) was served as the rigid side of the mould. A vacuum bag, which replaces the rigid upper half of the conventional RTM mould, acts as the cavity side of the mould. A set of consumables that consist of peel ply (PP80-1270), distribution media and channel, resin tubes and sealant tapes were used to construct the VARTM mould, as illustrated in Figure 3.2.

![Figure 3.2: Schematic diagram of VARTM](image)

### 3.1.3 Fabrication procedure

The fabrication procedure starts with the preparation of the mould for resin infusion. First, the glass panel surface was coated with layers of mould release agent to facilitate the removal of cured panel from the mould. Subsequently, the predetermined number of E-glass fibre mat layers (300 mm x 300 mm) was carefully stacked in the same fibre orientation for each layer on top of the glass mould to create a preform. 16 layers of fabrics were used to achieve the required laminate thickness and volume fraction.

The distribution media and distribution channel, *Enkachannel FPF100*, were placed on top of the preform as well as at both inlets and vents of the mould. This is to ensure uniform flow or distribution of the resin along the fibre direction as well as across the preform thickness. One layer of peel ply fabric was also placed in between the reinforcement and the distribution media which is to allow easy separation of the distribution media from the cured laminate. Then, the mould cavity was created by
Experimental Procedure

sealing the heat resistant vacuum bag (Nylon VFHT50G-2030) around the preform using sealant or ‘tacky’ tapes.

Strict procedures were followed to ensure that the mould cavity was properly sealed prior to the application of vacuum pressure. This is to alleviate any creation of bubbles or voids inside the laminates during resin infusion due to a leak in the vacuum bag or mould cavity. Once it has been confirmed that the bag was well sealed, a vacuum was applied to compact the dry preform, as depicted in Figure 3.3. Initially, the vacuum pressure driven from the Vacmobiles® vacuum pump was applied for 5 to 10 min to check for any possible leak during the dry compaction period. The mould cavity was left to equilibrate under the vacuum pressure once all possible leaks (which may be due to improper sealing) were eliminated. Upon complete mixing of the resin (mixture of epoxy and hardener at 4:1 ratio as recommended by the manufacturer) in the resin pot, the inlet gate was then opened to start the infusion.

![Figure 3.3: Dry compaction of the preform prior to resin infusion](image)

The full vacuum pressure (in the range of 5 to 10 mBar) during the infusion provides the driving flow force for the resin to impregnate the dry reinforcement as well as to maintain the compression force during compaction of the preform. This will result in the desired volume fraction of the composite panels. As soon as the resin flow reached the end of the preform, the inlet gate was closed while the resin was left to distribute throughout the dry preform under full vacuum pressure. The vacuum pressure was regularly monitored using an electronic pressure gauge to check for any possible leak during filling and post-filling. Average filling time of the thermosetting epoxy resin into
the mould cavity was recorded to be around 16 min. The infused panel was left to cure on the glass mould for a minimum of 12 hours at a room temperature. After de-moulding, further post-curing of the panel was performed at the oven temperature of 60 °C.

The part thickness of the fabricated laminates was measured to be $6.0 \pm 0.5 \text{ mm}$. The laminate was then cut into plates of 200 mm x 135 mm at the required fibre orientation using a 'water-cooled' diamond saw for the subsequent end milling experiments. Cap screw holes were drilled into the plate, as seen in Figure 3.4, for secure mounting during machining experiments.

![Figure 3.4: GFRP plate for the end milling experiments](image)

3.1.4 Specimen characterisation methods

The fabricated laminates undergo several characterisation experiments to ensure the quality consistency of each batch manufactured as well as to determine their important mechanical properties. This includes tensile testing, burn-off experiment, and scanning electron microscopy. The characterisation experiments were performed on randomly selected samples to evaluate the tensile properties, volume fraction, density and morphology of the laminates.
(A) Mechanical testing
Five rectangular tensile specimens of 250 mm x 15 mm were prepared from different samples of the fabricated GFRP panels according to ASTM D3039/D. The tensile testing was carried out at room temperature using the 100kN Instron® 1185 Universal Testing Machine. An extensometer of 50 mm gauge length was used to measure the stiffness of the samples. Strips of sandpaper were placed between the grips and the specimen to alleviate any slippage during testing due to stress concentration at the edge of the grip. The crosshead speed was given an initial strain rate of 0.01 min⁻¹, which then increased to 2 mm/min once the extensometer was removed. The tensile strengths for 5 selected batches of different laminates, depicted in Figure 3.5, reveal that the GFRP composites have acceptable variations in strength. Table 3.2 reports the overall results of the typical tensile properties which are based on the average data of the different laminate batches produced or selected. It can also be seen that the GFRP composites fabricated exhibit a very close value (with respect to tensile properties) to those reported in the literature as tabulated earlier in Table 2.4 of Chapter 2.
Table 3.2: Average value of important properties for the GFRP panels

<table>
<thead>
<tr>
<th>Typical Properties of GFRP Composites</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate tensile strength in fibre direction</td>
<td>692(± 10.17) MPa</td>
</tr>
<tr>
<td>Tensile modulus in fibre direction</td>
<td>33 (± 0.61) GPa</td>
</tr>
<tr>
<td>Tensile modulus in transverse direction</td>
<td>10 (± 0.23) GPa</td>
</tr>
<tr>
<td>Mass density</td>
<td>1.88 (± 0.0064) g/cm³</td>
</tr>
</tbody>
</table>

(B) *Volume fraction experiment*

It is known that combinations of fibre and resin content affect not only the laminates mechanical strength, but also their machinability. Consistent fibre and resin content on each of the laminates produced are essential in order to minimise the variability during machining experiments. Therefore, the burn-off test (according to ASTM D3171-09) was employed to evaluate the volume content of the fabricated laminates. Five samples (25 mm x 25 mm) from different batches of the fabricated laminates were randomly chosen and prepared for the burn-off test.

![Figure 3.6: The electrical furnace used for the burn-off test showing test specimens (a) before and (b) after experiment](image)

Initially, the mass of the samples with the crucible was measured to the nearest 0.1 mg using mass scale. The samples were then placed in the **Nobertherm** electrical furnace,
as depicted in Figure 3.6, in which the heating element was maintained at 565 °C for a minimum of 5 hours. This is to ensure uniform, moderate rate and complete charring of the thermosetting epoxy resin. After the tests, only fibre reinforcements were left, as shown in Figure 3.6 (b). The remaining fibre reinforcements were measured to the nearest 0.1 mg for volume fraction calculation. Once relevant parameters have been measured, the reinforcement content expressed as volume percentage was calculated using *Eq. 3.1* (based on ASTM D3171-09):

\[
V_f = \frac{M_f}{M_i} \times 100 \times \frac{\rho_c}{\rho_f}
\]

*Eq. 3.1*

where:

- \( M_i \) is the initial mass of the specimen;
- \( M_f \) is the final mass of the left over specimen after combustion;
- \( \rho_c \) is the density of the specimen;
- \( \rho_f \) is the density of in the reinforcement;

The variations of volume fraction for different batches of laminates produced, Figure 3.7, indicates that the calculated volume fraction of the samples ranged from 50.4% to 53.4%.

![Figure 3.7: Fibre volume fraction data for different batch of laminates produced](image)
Judging from this result, it can be implied that the laminates produced for the end milling experiment has an acceptable and consistent quality with respect to volume fraction or fibre content. The average value of the fibre volume fraction considering all of the tested samples was calculated to be 51.6%. The density of GFRP specimens was measured using Sartorius® Density Kit according to water displacement principle. The average of density value is given in Table 3.2.

3.1.5 Scanning electron microscopy

Prior to quantitative machining tests of GFRP samples, an initial qualitative inspection of the sample produced is required to verify the fabrication quality consistency. This was performed through the electron microscopy. SEM is a widely used tool to study the surface morphology or topography of a material by producing highly magnified images. Excitation of electron beams on the surface of a specimen produces combinations of high magnification and resolution images which are unattainable by the traditional optical microscope. The electron beam scans over the specimen in a series of lines and frames known as ‘raster’. With a large depth of focus, a three-dimensional appearance or characteristic is possible, which makes it useful in understanding the surface structure of a specimen.

The investigation of the composite laminates surface morphology, as well as the machined surface, was performed using the FEI Quanta 200F. This machine is also fitted with a lithium drifted Energy Dispersive X-ray Spectroscopy (EDS) detector. Samples from the manufactured laminate were carefully cut into the required size at the cross-section using a hand hacksaw. Any debris or dust produced during trimming was removed by blowing steady air onto the surface. This is to ensure accurate representation of the surface morphology of the samples under the SEM.

The Polaron SC 7460 sputter coater was used to coat the SEM samples with platinum at 5-10mA, 1.1kV and 300 s. Figure 3.9 exhibits the SEM micrographs of the laminate sample revealing the fibres and matrix phases of the composite. It appears that the glass fibre bundles are in-homogeneously bonded and impregnated with the thermosetting epoxy resin. Minimal formation of voids can also be detected, possibly a result of
incomplete resin impregnation, Figure 3.9 (b). Apparently, these voids may not extremely be of much influence on the machining experiments.

Figure 3.8: The FEI Quanta 200F and prepared GFRP samples for SEM characterisation
Figure 3.9: SEM images of cross-sectioned composite laminates
3.2 Experimental Equipment and Procedure

The overall schematic diagram of machining experimental set-up for this research is shown in Figure 3.10. Detailed discussions on the end milling machine, data acquisition equipment, procedure and finally the cutting tools are given in the subsequent section.

![Schematic diagram of overall machining experiments set-up](image)

3.2.1 CNC milling machine

All end milling tests were performed on the **Centroid 1050A** CNC vertical milling machine of 28 kW power, maximum spindle speed of 8,000 RPM with 3 linear and 2 rotary axes, Figure 3.11. This CNC milling centre is versatile and highly rigid that include multifunctional use for milling, drilling, taping and some basic turning processes. The wide machinable envelope or area of 1000 mm x 500 mm makes this machine capable of machining medium size components which are commonly used in industry.

All of the machining experiments were conducted under dry cutting conditions. With regard to this, a vacuum cleaner was used to handle the dust-like and hazardous chips.
produced during machining. This is to minimise chip interference that could lead to local heat accumulation in the cutting zone. In addition, this was carried out as a safety precaution for the machine operator and to avoid damage to the guide-ways of the CNC machine due to the highly abrasive and fine glass fibre chips. Specially written CNC code was programmed to facilitate the table/tool movement in which a slot or groove is created after each end milling pass, resulting in a full immersion cutting, Figure 3.12. The full immersion of the tool provides an up cut milling during tool edge entrance whilst down milling as the tool edge exits the workpiece material. This allows the study of difference morphology of the milled surface on the basis of tool sharpness and cutting mechanisms.

Figure 3.11: The CNC machine centre with Centroid controller

Figure 3.12: Full immersion cutting with up cut and down milling action of the cutting tool (cross-section view)
3.2.2 Data acquisition equipment and procedure

During the experiments, machinability data such as machining forces, tool wear and surface roughness were continuously acquired using dedicated equipment discuss in this section. As the basis for accurate analysis and modelling of the experimental results, a strict and systematic data acquisition was followed.

(A) Force dynamometer and measurement

Forces during machining were measured in the x direction ($F_x$ – feed force), y direction ($F_y$ – cutting force) and z direction ($F_z$ – thrust force) by means of a 3-axis piezoelectric dynamometer (Kistler®, Model: 9265B). This highly rigid dynamometer consists of four 3-component force sensors fitted (under high pre-load) between the base plate and the top plate. Each sensor contains three pairs of highly sensitive quartz plates in detecting pressures in the X, Z, and Y directions respectively.

This dynamometer was firmly mounted on the machine bed; while the composite laminate was directly placed on top of the dynamometer and secured tightly using cap screws, Figure 3.13 (a). During the machining, the cutting was performed so that the feed direction of the machine table was in the positive x direction of the dynamometer force measurement system, Figure 3.13 (a).

Figure 3.13: (a) Force measurement directions on the dynamometer and (b) Kistler® charge amplifier and PC with LabVIEW® for data acquisition
The machining force signals generated during the milling experiment were fed into a 3 channel charge amplifier (Kistler®, Model: 5001) for conversion of electrical charges into voltages. The amplified voltages were then passed through a National Instrument data acquisition card (NI-DAQ, Model: NI PCI-MIO-16XE-50) in which the signals were sampled and digitised at a sampling rate of 100 Hz. The digitised signals were acquired using a Pentium IV PC with National Instrument LabVIEW® software V8.2, Figure 3.13 (b). Subsequently, the signal conversions and analyses were performed in Microsoft® Excel spreadsheet. It is to note that the Kistler® charge amplifier would need to be reset after each in order to alleviate the drift in the measurement of force.

(B) Calibration and signal processing

Prior to machining tests, the Kistler® dynamometer with the charge amplifier were calibrated under quasi-static load on the Instron® 1185 Universal Testing Machine, to ensure accuracy in the acquired force data. The sensitivity of the Kistler® charge amplifier and the conversion scale were set according to manufacturer recommendations given in Table 3.3. Results of the calibration curves are as illustrated and given in Appendix 3-1.

<table>
<thead>
<tr>
<th>Force Components</th>
<th>Sensitivity settings</th>
<th>Conversion Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed force ($F_x$)</td>
<td>7.86 pC/N</td>
<td>100 N/volt</td>
</tr>
<tr>
<td>Cutting force ($F_y$)</td>
<td>7.89 pC/N</td>
<td>100 N/volt</td>
</tr>
<tr>
<td>Thrust force ($F_z$)</td>
<td>3.69 pC/N</td>
<td>100 N/volt</td>
</tr>
</tbody>
</table>

High degrees of frequency or fluctuation in the machining force data can be observed during machining due to the anisotropic and non-homogeneous nature of fibre-reinforced materials. As a result, the machining data were sampled in order to remove extraneous peak forces. As an example, Figure 3.14 exhibits the machining force data (in the feed direction, $F_x$) measured during a single end milling pass.
These signals were processed under time domain by monitoring the feed motion of the cutting tool from the time the tool tip entered the workpiece material until the tool exit the material. Initial time, $T_i$ as the tool enters the material can be determined at the point where plot of the machining force versus time experience a sudden and continuous positive slope over a short-duration time. Likewise, final time, $T_f$ is when a sudden and continuous negative slope was observed as the tool exits the workpiece material. The force development during a single machining pass encompasses three regions, Region 1 – 3, as depicted in Figure 3.14. Region 1 is when the machining force increases sharply which represents the engagement of the tool into the workpiece material. Steady state machining is established as the tool progressing through the material, Region 2. Finally, Region 3 is where the tool is exiting the material.

The difference between $T_f$ and $T_i$ represents the total machining time of one end milling pass. A 100 point moving average was performed on the raw force signal to show realistic trends in the force measurement, depicted as the superimposed ‘red dotted’ line in Figure 3.14. This technique significantly reduces the possible noise in the raw data by
attenuating the force signals. The average of those filtered values is taken as the final force measurement for further analysis.

(C) Tool wear measurement and tool life criterion
Apart from measuring machining forces, another important aspect of this research is to monitor the extent of tool wear and estimate the total machining time required until the tool reaches the pre-defined wear criterion. Figure 3.15 shows a typical schematic diagram of tool wear measurement area on the tool tip. To facilitate the possibility of regrinding of the end mill tool, the machining experiment is stopped when the followings are exhibited:

- reach maximum uniform flank wear, \( VB_{\text{max}} \) of 0.3 mm on any cutting flute, or
- reach an average flank wear, \( VB \) of 0.3 mm on all four cutting flutes, or
- excessive edge, nose deformation/rounding or chipping on more than 2 cutting flutes.

![Flank wear height on the tool flank face](image)

Figure 3.15: Typical criterion used for measurement of flank wear, \( VB \) [170]

Based on the aforementioned criteria, the total machining time is recorded as the useful life of a cutting tool for subsequent machinability evaluations. The progression of tool wear on the clearance/flank face of the end mill cutter was monitored under the optical
Experimental Procedure

A stereo microscope, **Leica, Model: MZ16** at x115 magnification, Figure 3.16. This microscope is equipped with a digital camera to enable digital pictures to be taken for further analyses. Prior to measurement of the tool wear under the microscope, calibration of the microscope was undertaken by means of the standard scale.

The machining tests have to be interrupted at predetermined intervals appropriate to the machining parameters as well as the rate of tool wear, in order to capture images of the wear land on the end mill cutter. Commercially available UTHSCSA Image Tool® software was then used to measure the width of wear land on each of the cutting flutes from the images. An average of those measured widths was taken to be the tool flank wear after a period of machining time. In addition to the optical microscopy, detail examinations of wear mechanisms are carried out using the SEM with EDS capability.

![Figure 3.16: Leica MZ16 optical stereo microscope for tool wear measurement](image)

**Figure 3.16**: Leica MZ16 optical stereo microscope for tool wear measurement

**(D) Surface roughness measurement**

The perceived machining qualities determine by the surface roughness, delamination damage, severity of the fibre pullout and matrix failure, need to be critically quantified for the final applications of GFRP composites. Surface finish quality is largely influenced by the extent of tool wear and chip formation mechanism, apart from machining parameters [79]. Surface finish evaluations were performed on different surfaces of the milled grooves. As recommended in [84], the centre line average roughness, $R_a$, was employed to measure the roughness on the surface of the milled grooves under different machining parameters tested.
The Taylor Hobson Surtronic-3 measurer with diamond stylus tip was used for the surface roughness measurement, Figure 3.17. This measurer was set at 5 mm traverse length and 0.8 mm cut-off value. The surface roughness was measured at five equally spaced positions, Figure 3.18. Measurements were also repeated (at least three times) to minimise experimental variations. Similar to that of tool wear measurement, calibration of the surface roughness measurer was undertaken using a reference specimen as shown in Figure 3.19. As depicted by the arrow in Figure 3.19 (a), the measured $R_a$ for the reference specimen is 2.86 $\mu$m, which is close to the reference value of 3 $\mu$m.
Experimental Procedure

3.2.3 Selection of cutting tool

Selection of the cutting tool materials is one of the most critical aspects in any machining process. Referring to Chapter 2, four families of cutting tool materials, namely high speed steel (HSS), cemented carbides, ceramics (sintered based alumina, Al₂O₃) and ultra-hard materials (natural and synthetic diamonds) are commercially available for various machining applications. These classifications are based on the hardness, strength and toughness of the material, Figure 3.20 [3]. Hardness of a cutting tool describes the ability of the cutting tool material to resist abrasive wear during machining. On the other hand, toughness is the ability of the cutting tool to resist fracture under heavy and/or intermittent loads while cutting is in operation.

An ideal tool, which have the combinations of both properties and designed to machine any materials, has yet to be discovered [3]. With a wide variety of cutting tool geometries and materials available in the market, those suitable for machining FRP composites should possess several characteristics. These characteristics include extreme hardness, excellent thermal conductivity, and with specific-geometry. This is particularly vital in order to withstand the abrasive actions from the fibre reinforcement. It is well acknowledged that most of the commonly used tools for machinability studies of materials range from tungsten carbides (uncoated or coated) to diamond coated (CVD) and polycrystalline diamond (PCD) tools. PCD is the most superior in sustaining longer tool life. However, the high cost of this tool hindered it being used for this research.

Figure 3.19: \( R_a \) measurement for the reference specimen
Experimental Procedure

As a matter of fact, the use of PCD tool is only extremely beneficial during high-speed machining (as previously elaborated in Chapter 2), which is not the case for this thesis. This study employed the typical range of parameters used in industries as well as within the limits of the CNC machine. It is imperative to note that there is no evidence which shows superior performance of the coated carbide tools compared to that of the uncoated tool when machining composite materials [67, 68]. Coated carbides such as TiN, TiC and TiAlN are not favourable due to their tribological behaviour. The coating also causes the cutting edge radius to increase, which means that the tool becomes more rounded or blunt. Low fracture toughness, poor thermal conductivity, and relatively weaker interlayer adhesion of the coating on the carbide substrate also limit the application of the tools for machining composite materials [68, 171]. Hence, in line with those reported in the literature [29, 128, 172], the uncoated cemented carbide helical end mill cutter, EDP41665 supplied by SGS Tools Inc. was selected.

The tool is K20 micro-grain grade containing 94% tungsten carbide, WC (average 1.7 μm grain size) while the rest is Cobalt, Co, binder. This general purpose end mill cutter is commonly used in industries and can be quickly re-conditioned once the tool sharpness has deteriorated. A tool holder, BT40XFR40-80, was used with a spring-type collet to lock the end mill tool. After each removal of the tool from the holder (for the tool wear measurement), a tool height setter, Centroid TT1 was used to reset the height.
of the end mill tool, Figure 3.21 (b). This is to ensure consistent reference between the workpiece material and the tool off-set value during each machining pass.

(a)

![Image](image1.png)

(b)

![Image](image2.png)

Figure 3.21: The uncoated tungsten carbide end mill tool used for this experiment

Table 3.4: Specifications of the end mill tool

<table>
<thead>
<tr>
<th>Items</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade</td>
<td>K20 (94% WC)</td>
</tr>
<tr>
<td>Diameter, overall length</td>
<td>12 mm, 75 mm</td>
</tr>
<tr>
<td>Number of flutes, flute length</td>
<td>4, 25 mm</td>
</tr>
<tr>
<td>Helix, relief and clearance angle</td>
<td>30°, 9°, 16°</td>
</tr>
</tbody>
</table>

Figure 3.22 exhibits the SEM images of one of the end mill cutting flutes prior to machining experiments. The details of this end mill cutting tool can be found in Table 3.4 and Appendix 3-3.

(a)

![Image](image3.png)

(b)

![Image](image4.png)

Figure 3.22: SEM images of the end mill tool
3.3 Summary

This chapter has presented the details of the GFRP composites manufacturing, along with the equipment and procedure employed during the machining experiments. The conclusions that can be drawn are as follows:
- The GFRP composite panels for the end milling tests have been successfully manufactured using VARTM process.
- The test panels have been characterised using mechanical, burn off test as well as scanning electron microscopy to verify the consistent quality of the laminates produced.
- Set-up and data acquisition methods for various subsequent machinability tests have been developed and finalised.
4.1 Introduction

As discussed in Chapter 2, various conventional machining processes, namely turning, drilling and milling have been used to machine composite materials in order to meet their different geometrical requirements and control dimensional tolerances. Despite the existing experience and knowledge in machining homogeneous materials such as metals, it has been a challenge to maintain consistent results in terms of machining quality and performance for composite materials, particularly the FRP composites.

Summarising on some of the reported studies while milling FRP composites, it can be concluded that a complete milling machinability evaluation for GFRP composites using a proper ‘design of experiment’ technique has not been fully or adequately addressed. Earlier, the literature review chapter has elaborated that Puw and Hocheng were the first to investigate the milling machinability of uni-directional CFRP composites [111, 173]. However, the results of their study were purely experimental. Until recently, only a handful of researchers have reported experimental results on limited aspects of FRP’s milling machinability indices, such as machining forces and delamination damage [112-114, 116, 121, 123-125]. For instance, Davim et al. showed some promising results with regard to surface quality and delamination damage while milling woven type FRP composites [113-115], yet, their studies were limited to only two machining parameters, namely, the feed rate and cutting speed.
Apart from that, the performance of other machinability response or indices, such as tool wear and tool life, were not disclosed. In recent studies, Karpat et al. and Sheikh Ahmad et al. have developed a mechanistic force prediction model during end milling of uni-directional CFRP composites with different fibre orientations [117, 118, 121]. In spite of the extensive results discussed, their studies were limited to relatively lower range of machining parameters and did not consider the effect of tool wear. Therefore, this chapter addresses some of the previous research limitations pertaining to machinability of FRP composites. It specifically discusses the results of parametric study during end milling of uni-directional glass fibre-reinforced polymer composites. The primary objective is to determine the factorial effects of the selected machining parameters on the key machinability outputs. This has been achieved through Taguchi design of experiment methodology, in which carefully designed trials of different experimental factors and levels have been considered.

4.2 Design of Experiments

Extensive and expensive experimentations (e.g. time, labour, materials, etc.) would typically be required to evaluate the machinability of a material. Hence, the experimental approach of machinability assessments can be well achieved through statistically designed tests or experiments, commonly known as the DOE. This methodology allows full factorial experimentation as well as partial or fractional experimentation. Although full factorial experiments may provide all the possible effects of experimental factors together with their interactions, the scale of experimentations can be prohibitive for scientific investigations. Realistically, fractional factorial approach through the Taguchi methodology, which involves significantly fewer tests but with highly acceptable and reliable results, would be more attractive.

4.2.1 Taguchi method

Taguchi method is an immensely popular statistical DOE approach that has been employed in diverse engineering applications. In this methodology, experiments are systematically planned according to a specifically designed orthogonal array (OA) that can reduce the number of experiments [174]. Within a column of an array, each factor
has an equal number of levels or appears at equal number of times. The arrangement of an OA can also accommodate a number of experimental factors to allow the study of their effects and interactions on the experimental output simultaneously. Very often, Taguchi method permits the optimisation of the process parameters while minimising the sensitivity to various sources of experimental variations.

4.2.2 Experimental layout and selection of machinability parameters

The unique characteristics of GFRP composites affect their machinability differently from those of the homogenous materials. Based on literature search discussed in Chapter 2, physical properties of GFRP composites; e.g. fibre orientations and types, volume fractions, and matrix material, greatly influence the machinability of these composites apart from the processing and tooling parameters. The processing and tooling parameters, on the other hand, can include spindle or cutting speed, feed rate and depth of cut, tool materials and their geometries. Such a large number of influencing factors add to the complexity of experimental investigations.

In this part of the work, only machining or processing parameters are considered for the parametric analysis of their significant influence. In fact, the results of this parametric analysis are used to reduce the number of machining parameters to facilitate the future work on developing machinability prediction model, which takes into account the most important parameters. It is worthwhile to emphasise that the end milling operation was performed along the fibre or table/tool feed direction, \( x \), previously shown in Figure 3.13. As outlined earlier, workpiece material used was the uni-directional E-glass fibre-reinforced epoxy matrix. Machining was performed under dry condition or without any coolant using the uncoated tungsten carbide cutting tool.

Primary objective of the present work is to elucidate/understand the effect of machining parameters on three machinability outputs, e.g. surface roughness, resultant machining force and tool life. This has been achieved through the Taguchi DOE methodology. Different levels of low, designated as (1), medium (2) and high (3), for each parameters, Table 4.1, encompassing a typical range of machining parameters employed in the industry, were selected for experimentation.
The justifications for selecting those parameters and three levels settings were twofold:

(1) To incorporate all possible processing parameters and their respective ranges, and
(2) To investigate any nonlinear effects these parameters have on the key machinability output.

It is to be noted that the operating window for the current machining tests was selected according to the importance of industrial applications as well as within the limit of the CNC machine tool. The selected range of machining parameters was also deliberately set higher than those typically reported in literature [112-114, 116, 125].

Cutting or spindle speed is known to have significant influence on the extent of tool wear and surface roughness, particularly in metal cutting. Initially during a preliminary test, the spindle speed was set at 2,000 RPM. However, this resulted in a premature failure of the cutting tool with chipping on the tool edges. Partially, this could be due to the nature of intermittent or discontinuous cutting action in milling as the tool encounters in-homogeneous layers of fibre reinforcement and epoxy matrix. It is worth noting that the speed of lower than 2,000 RPM is deemed to be low as far as machining productivity is concerned. On the other hand, a higher spindle speed of above 6,000 RPM leads to rapid tool wear. Consequently, a rotations speed of 3,000–5,000 RPM was set as suitable test range for the spindle speed.

As indicated in the previous studies [111, 113, 114, 116], the employed feed rates were reported to be within the range of 200–800 mm/min when milling CFRP composites. The selection of feed rate range during machining is critical because it determines the surface quality of the machined components. A value less than those reported in the literature would diminish machining productivity, whereas a higher value would accelerate heat generation, increase machining forces and enhance the tool wear. The reduction of tool sharpness deteriorates the surface quality; as a result, the 500–1,000 mm/min range of feed rate was found to be appropriate. It is necessary to highlight that although the depth of cut plays a small role during metal machining, its range was selected to be 1–2 mm. In fact this range is in accordance with previous studies on machining or end milling CFRP composites.
Table 4.1: Experimental parameters and their levels

<table>
<thead>
<tr>
<th>Factors/Level</th>
<th>Level 1 (Low)</th>
<th>Level 2 (Medium)</th>
<th>Level 3 (High)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Feed rate, $f$ (mm/min)</td>
<td>500</td>
<td>750</td>
<td>1,000</td>
</tr>
<tr>
<td>B: Spindle Speed, $s$ (RPM)</td>
<td>3,000</td>
<td>4,000</td>
<td>5,000</td>
</tr>
<tr>
<td>[Cutting Speed, $v$ (m/min)]</td>
<td>110</td>
<td>150</td>
<td>190</td>
</tr>
<tr>
<td>C: Depth of cut, $a_p$ (mm)</td>
<td>1</td>
<td>1.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>

In the traditional full factorial experimentation, 27 trials would be needed to complete the entire experimental work of three factors at three levels. However, based on the selected parameters and their levels, the parametric study could well be performed using the $L_9$ Taguchi OA. Under this OA, nine experimental runs would be required to complete the array. Hence, the Taguchi experimental layout is arranged according to Table 4.2 with each trial performed in a random order so that any chances of systematic error during measurement of the machinability outputs can be minimised. Interactions of the main factors (factors with the highest percentage contribution from the Pareto ANOVA analysis) were also considered. It is vital to note that the effects of factorial interactions are normally marginal based on reported studies of the others (under a different domain of machinability tests) [91].

Table 4.2: Parametric combinations for the $L_9$ end milling trials

<table>
<thead>
<tr>
<th>Trial No</th>
<th>Random No</th>
<th>Machinability Parameter Level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Feed Rate, A</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>2</td>
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<tr>
<td>5</td>
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<td>2</td>
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<td>8</td>
<td>3</td>
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<tr>
<td>8</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
Taguchi recommends the average value of experimental response and its corresponding signal to noise ratio ($S/N$) of each experimental run in order to analyse the effects of each experimental parameter [175, 176]. Typically, the application of $S/N$ ratio in the Taguchi analysis is to determine a robust setting of experimental parameters so that the product or process variables insensitive to the noise factors. $S/N$ ratio has been chosen for the Taguchi analysis because it represents both the average (mean) and variation (standard deviation) of the experimental results [174-176]. Depending on the qualitative characteristics of the experimental output, the $S/N$ ratio can take up either ‘the lower the better’ or ‘the higher the better’ category, given as:

\[
\text{The lower the better: } S/N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} x_i^2 \right) \quad \text{Eq. 4.1}
\]

\[
\text{The higher the better: } S/N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{x_i} \right) \quad \text{Eq. 4.2}
\]

where $n$ is number of measurements in each trial, and $x$ is the machinability output of $R_a$, $F_m$ or TL.

### 4.3 Results and Discussion

Figure 4.1 (a) displays the average $R_a$ values for each of trial carried out based on the Taguchi L9 experimental layout. These average values were calculated from the number of $R_a$ readings measured according to procedure explained in Chapter 3. The bar graph shows that the best attainable surface roughness is when the parameters were set according to the parameters in Exp 3 (at A1B3C3), in which the value of $R_a$ is 1.80 $\mu$m. Conversely, the highest $R_a$ value of 2.69 $\mu$m can be observed in Exp 4. It is worthwhile to mention that $R_a$ was measured along the fibre and tool feed directions, $x$ in Figure 3.13, as recommended in [84].

Figure 4.1 (b) presents variations of the measured feed force, $F_x$ (refer to Figure 3.13), from each experimental trial. Each of these force values is based on the average of three force measurements while milling for 200 mm length. Such procedure was taken to alleviate the effect of tool wear on the force measurement. Appendix 4-1 shows the
results for the other force components, cutting force, $F_y$, and thrust/normal force, $F_z$. It is to note that each of the measured machining force components was combined into resultant machining force, $F_m$, to facilitate the Taguchi analysis. The expression for $F_m$ is given as [113, 114]:

$$F_m = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad \text{Eq. 4.3}$$

Figure 4.1 (c) displays the variations of $F_m$ from each experimental trial that shows the highest machining force of 91 N can be observed in Exp 8 whereas the lowest, 21 N, in Exp 1. It should be noted that the error bars represent standard deviations of repeated measurements of surface roughness and machining forces. Using ‘the lower the better category’, values of $S/N$ ratios for $R_a$ and $F_m$, were calculated using Eq. 4.1 for the Taguchi analysis. This $S/N$ category is chosen to reflect lower values for both $R_a$ and $F_m$ are more desirable in this parametric study. The results of Taguchi analysis for these machinability indices are further discussed in the subsequent sections.

As far as the tool performance is concerned, Figure 4.2 exhibits a collection of photos taken from the Leica MZ16 optical microscope that illustrate the extent of tool wear on the flank face of the end mill tool. This result is based on the machining parameters in Exp 4. Uniform scratch marks can be observed on the flank face of the cutting tool that indicates the tool wear mechanisms during machining. The tool wear mechanisms are discussed in the forthcoming section.

The plot of tool wear, $VB$, against machining time follows the typical tool wear curve that consists of the ‘break in period’, ‘steady state wear’ and finally ‘rapid wear’, Figure 4.2. The combined tool wear curves for all tests conducted according to L9 Taguchi array are displayed in Figure 4.3. In most of the cases, flank wear increases progressively with machining time. Using tool life criterion of 0.3 mm average flank wear, the estimated tool life, TL ranges from the longest of 940 s or 15.67 min (Exp 1) to the lowest of 140 s or 2.33 min (Exp 8).
Figure 4.1: Measured $R_a$, $F_x$ and calculated $F_m$ from the L9 DOE experiments.

### Table

<table>
<thead>
<tr>
<th>Surface Roughness ($R_a$, μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Feed Force, $F_x$ (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resultant Force, $F_m$ (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
</tbody>
</table>
Figure 4.2: Optical microscope photos of typical tool wear growth and the curve of tool wear growth against machining time for experimental parameters of A2B1C3

In general, the range of tool life is adequate when compared to those reported in the literature for uncoated tungsten carbide tool. A previous study of milling CFRP composites has found that the tool life of the single square carbide insert was 16 min (960 s) for tool wear criterion of 0.6 mm when machining at relatively mild parameter of 3,000 RPM, 0.017 mm/per tooth and 1 mm depth [111]. Unlike $R_a$, and $F_m$, Eq. 4.2, was used for the tool life according to ‘the higher the better’ category of the S/N ratio, which indicates that longer or higher tool life is required for optimum machinability performance.
4.3.1 Evaluation of significant factors through statistical analyses

Table 4.3 displays the complete experimental results and the corresponding S/N ratios for $R_a$, $F_m$ and TL, respectively. Orthogonality of the experimental design makes it possible to isolate the effects of each machining parameters at different levels, using either average value of the experimental outputs or their corresponding S/N ratios. For this study, analyses on the effects of machining parameters were carried out using the S/N ratios of the machinability outputs through response tables and graphs, Pareto ANOVA and ANOVA table.

Response table and graph allow a direct identification of the parameter effects by observing the difference between the lowest and the highest S/N ratio values of the experimental outputs. The higher the difference implies a greater influence the factor has on the experimental output, whereas, a higher S/N ratio value always corresponds to more robust quality characteristics of each machinability output regardless of the category, Eqs. 4.1 & 4.2.
Table 4.3: Experimental results for $R_a$, $TL$ and $F_m$ with their corresponding $S/N$ ratios

<table>
<thead>
<tr>
<th>Exp No</th>
<th>Factors &amp; Levels</th>
<th>Experimental Response and Calculated S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
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<td>2</td>
<td>1</td>
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<td>2</td>
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<tr>
<td>9</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Pareto ANOVA, which is a simplified Analysis of Variance (ANOVA) method, provides a quick and easy way to determine the contribution effect of each parameter has on the experimental output. This can be achieved by constructing a Pareto diagram. The Pareto ANOVA uses 80/20 principle, which means that 80 percent of the effects come from 20 percent of the causes [174]. A general criterion in determining the significant factors is based upon the derived cumulative contribution percentage of about 90%. Although the percentage contributions of experimental factors can be easily determined through the Pareto ANOVA, this approach simplifies the statistical analysis without incorporating the Fisher test or $F$-test.

Based on the aforementioned discussion, it is unknown how much error is associated within the experimentation. This problem can be resolved by using the traditional ANOVA methodology developed by Fisher [174, 177]. ANOVA allows quantification of the significance of experimental factor by comparing the mean square error of the main factors against an estimate of the experimental errors, at a specific confidence
level [174, 177]. The comparison of $F_{ratio}$ (ratio of the factor variance to the error variance) with the critical Fisher ratio, $F_{crit}$ (which is determined from F distribution table), can be used to show the significant factors in the experimental design. Factors having $F_{ratio}$ above the $F_{crit}$ are regarded as highly significant, whereas factors with levels less than the $F_{crit}$ are deemed insignificant or weakly significant at the predefined confidence level. Results from the aforementioned statistical analyses; namely $S/N$ ratio, Pareto ANOVA and ANOVA, are discussed in the subsequent sections. It is to note that Appendix 4-2 lists the complete Taguchi supplementary data used herein.

(A) Results of statistical analyses for $R_a$

Response graph of the $S/N$ ratio, Figure 4.4 (a), displays the effects of changing machining parameters on surface roughness, $R_a$. It is apparent that combinations of feed rate and spindle speed have, expectedly, the strongest effect on $R_a$, with feed rate being the dominant factor at 75% contribution, as shown in the Pareto ANOVA plot, Figure 4.4 (b). In contrast, spindle speed has the percentage contribution of 22%. The results also suggest that both of these parameters greatly influence the surface roughness with cumulative percentage of beyond 90%. From the response graph, Figure 4.4 (a), it is implied that low feed rate, A1 and high spindle speed, B3 are preferred for improving the surface finish of the machined GFRP composites. The small difference between the minimum and the maximum $S/N$ ratios for the depth of cut, Figure 4.4 (a) and Table 4.4, indicates that the effect of this parameter on $R_a$ is trivial. As depicted in the Pareto ANOVA, the percentage contribution was only about 3%, Figure 4.4 (b).
The depth of cut can be set at the low level, C₁, for better surface finish, as shown in response graph, Figure 4.4 (a). This result substantiates some of the previously reported findings while turning composite materials [91, 178-180], which emphasised the negligible or small effect of depth of cut on $R_a$. Overall, the robust setting to achieve minimum value of $R_a$ for this parametric study is at A₁B₃C₁. Although results from the response graph and Pareto ANOVA are capable of showing the different effects of machining parameters on $R_a$, the relative importance or significance among different machining parameters need to be critically evaluated.

This can be achieved through $F$ test of the analysis of variance. The results in Table 4.5 further confirm that the change in depth of cut has no considerable effect on $R_a$. The small value of $F_{ratio}$ for depth of cut warrants it to be pooled with random error associated with the experimentation. From Table 4.5, the value of $F_{ratio}$ and the contribution (%) indicate that feed rate has the highest statistical significance on the $R_a$. The influence of the spindle speed is deemed to be weak on the $R_a$, judging from the $F_{ratio}$ value as well as the % contribution.

### Table 4.5: ANOVA results for $R_a$ based on S/N ratio

<table>
<thead>
<tr>
<th>FACTOR/RESPONSE</th>
<th>SS</th>
<th>DF</th>
<th>MS</th>
<th>$F_{ratio}$</th>
<th>% Contribution</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>6.01</td>
<td>2</td>
<td>3.00</td>
<td>9.13</td>
<td>66.27</td>
<td>Highly</td>
</tr>
<tr>
<td>B</td>
<td>1.74</td>
<td>2</td>
<td>0.87</td>
<td>2.65</td>
<td>19.22</td>
<td>Weakly</td>
</tr>
<tr>
<td>C</td>
<td>(0.24)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>No</td>
</tr>
<tr>
<td>Error</td>
<td>1.32</td>
<td>4</td>
<td>0.33</td>
<td>-</td>
<td>14.51</td>
<td>-</td>
</tr>
</tbody>
</table>

**TOTAL** | 9.07 | 8  | 0.33 | -           | 100.00         |              |

*Note: SS: sum of square; DF: degree of freedom; MS: mean squares; $F_{crit}$ at 2,4 = 6.94*
(B) Results of statistical analyses for $F_m$

The ANOVA results and Pareto histogram depicted in Table 4.6 and Figure 4.5 (b) indicate that feed rate and depth of cut contributed to the variation of the resultant machining force at 54\% and 46\%, respectively. Likewise, the plots displayed in the response graph, Figure 4.5 (a), verify these ANOVA results. The large differences between the lowest and highest values of the $S/N$ ratio for both feed rate and depth of cut suggest their strong effects on $F_m$. Apparently, a gentle increase in the $S/N$ ratio value for $F_m$ is noticeable as spindle speed increases, Figure 4.5 (a), which indicates its minor influence on $F_m$. This is evident in the ANOVA results, Table 4.6, in which the sum of square variation (SS) for the spindle speed is considered to be insignificant and pooled with the error associated with the experimentation.

Table 4.6: ANOVA results for $F_m$ based on $S/N$ ratio

<table>
<thead>
<tr>
<th>FACTOR/RESPONSE</th>
<th>SS</th>
<th>DF</th>
<th>MS</th>
<th>$F_{ratio}$</th>
<th>% Contribution</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>71.03</td>
<td>2</td>
<td>35.52</td>
<td>67.42</td>
<td>53.64</td>
<td>Highly</td>
</tr>
<tr>
<td>B</td>
<td>(0.72)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>No</td>
</tr>
<tr>
<td>C</td>
<td>60.33</td>
<td>2</td>
<td>30.17</td>
<td>57.26</td>
<td>45.56</td>
<td>Highly</td>
</tr>
<tr>
<td>Error</td>
<td>1.054</td>
<td>4</td>
<td>0.53</td>
<td>0.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>132.41</td>
<td>8</td>
<td>100.00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: SS: sum of square; DF: degree of freedom; MS: mean squares; $F_{crit \text{ at } 2,4} = 6.94$

Figure 4.5: (a) Response graph and (b) Pareto ANOVA for $F_m$ based on $S/N$ ratio
Although, previous studies \[113, 114\] have determined that feed rate has the largest influence on resultant machining force compared to that of spindle speed, the current work in this thesis, however, has highlighted that depth of cut is an equally dominant parameter that influence the $F_m$ during end milling of GFRP composites. From both response graph and table, Figure 4.5 and Table 4.7, the preferred condition for minimum machining forces is also at A_1B_3C_1.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level (S/N)</th>
<th>Max – Min</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-29.21</td>
<td>-36.09</td>
<td>6.87</td>
</tr>
<tr>
<td>B</td>
<td>-33.08</td>
<td>-32.39</td>
<td>0.69</td>
</tr>
<tr>
<td>C</td>
<td>-29.44</td>
<td>-35.76</td>
<td>6.32</td>
</tr>
</tbody>
</table>

(C) Results of statistical analyses for TL

Finally, feed rate has also demonstrated the highest influence on the time for the tool to reach the flank wear criterion of 0.3 mm (defined as the tool life, TL). Although increasing spindle speed is expected to accelerate tool wear and reduce the tool life, results from this study have shown that the increase in tool wear is minimal due to changes in the spindle speed. Percentage contribution of the spindle speed is only about 12% as compared to that of the feed rate at 87%, as shown in the Pareto ANOVA, Figure 4.6 (b). This is further verified from the ANOVA analysis, Table 4.8, which indicates the marginal or weak influence of spindle speed on TL.

This finding is somewhat unexpected and contradicts with some of the previous studies on drilling of CFRP and metal matrix composites \[65, 181\]. As reported, those studies found that cutting speed governed the time to reach the predetermined tool life criterion. It is imperative to note that the 3.51% error level associated with the experimentation, Table 4.8, is within the acceptable limit, suggesting that measurement of tool wear for tool life has been accurately performed. The anomaly of this result is further investigated and discussed in the next section.
Figure 4.6: (a) Response graph and (b) Pareto ANOVA for TL based on S/N ratio

Table 4.8: ANOVA results for TL based on S/N ratio

<table>
<thead>
<tr>
<th>FACTOR/RESPONSE</th>
<th>SS</th>
<th>DF</th>
<th>MS</th>
<th>F&lt;sub&gt;ratio&lt;/sub&gt;</th>
<th>% Contribution</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>211.35</td>
<td>2</td>
<td>105.67</td>
<td>48.58</td>
<td>85.16</td>
<td>Highly</td>
</tr>
<tr>
<td>B</td>
<td>28.12</td>
<td>2</td>
<td>14.06</td>
<td>6.47</td>
<td>11.33</td>
<td>Weakly</td>
</tr>
<tr>
<td>C</td>
<td>(2.24)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Error</td>
<td>8.70</td>
<td>4</td>
<td>2.18</td>
<td></td>
<td>3.51</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>248.17</td>
<td>8</td>
<td></td>
<td></td>
<td>100.00</td>
<td></td>
</tr>
</tbody>
</table>

Note: SS: sum of square; DF: degree of freedom; MS: mean squares; \( F_{crit} \) at 2,4 = 6.94

Table 4.9: Response table for TL based on S/N ratio

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level (S/N)</th>
<th>Max - Min</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>A</td>
<td>57.51</td>
<td>52.68</td>
<td>45.70</td>
</tr>
<tr>
<td>B</td>
<td>54.45</td>
<td>50.92</td>
<td>50.52</td>
</tr>
<tr>
<td>C</td>
<td>52.63</td>
<td>51.84</td>
<td>51.42</td>
</tr>
</tbody>
</table>

Expectedly, the effect of depth of cut on tool life is trivial, with the sum of percentage contribution being less than 1% as indicated in the Pareto ANOVA, Figure 4.6 (b) and Table 4.9. Similar to \( R_a \) and \( F_m \), a response graph, Figure 4.6 (a), was used to
determine the preferable condition for maximum TL during end milling of GFRP composites, which is at A1B1C1. Although this confirms the common expectation, this condition leads to lower output rates, which is not desirable as far as the machining productivity is concerned. Consequently, selections of preferable parameters should depend on end usage or final machining requirement as the cutting parameter that produces lower tool wear or highest TL may not give the highest production rate.

Summaries of the preferred parameter combinations for all machinability performances are shown in Table 4.10 along with their respective $S/N$ ratios and estimated error variance. It is worth highlighting that the statistical analyses reported herein focus solely on either minimisation or maximisation of the individual machinability output. The fact is that, globally optimised situation for enhancement of end milling GFRP composites would be difficult due to contradictory effects of each machinability outputs.

<table>
<thead>
<tr>
<th>Machinability outputs</th>
<th>$S/N$ Criteria</th>
<th>Factorial combination</th>
<th>Error variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface roughness, $R_a$</td>
<td>The lower the better</td>
<td>A1B3C1</td>
<td>0.33</td>
</tr>
<tr>
<td>Machining force, $F_m$</td>
<td>The lower the better</td>
<td>A1B3C1</td>
<td>0.53</td>
</tr>
<tr>
<td>Tool Life, TL</td>
<td>The higher the better</td>
<td>A1B1C1</td>
<td>2.18</td>
</tr>
</tbody>
</table>

Final judgment should also consider the end application or evaluation of end milling performance. It is either to improve the surface quality or to reduce the machining forces; or prolong the tool performance/life or increase the overall machining productivity. With the exception to $R_a$, it appears that the interactions effect of feed rate and spindle speed on $F_m$ and TL output are little as compared to that of the main parameters, Figures 4.5 – 4.6. This points out that the effects of machining parameters are independent of one another, particularly for $F_m$ and TL. The effects of main factors are further discussed in the following section of this chapter, section 4.3.2.
4.3.2 Interpretations and discussion on the parametric/factorial effect

For final applications of GFRP composites, the perceived machining quality determined by surface roughness value ($R_a$), delamination damage, severity of the fibre pullout and matrix failure, needs to be critically quantified. Previously presented statistical analyses of factorial effects suggest that the combinations of feed rate and spindle speed have significant effects on $R_a$. Figures 4.7 – 4.8 exhibit these different effects, in which it is clear that $R_a$ values deteriorated with the increase of feed rate. In contrast, some marginal improvement of $R_a$ is evident with respect to a higher spindle speed.

The effect of changing feed rate on $R_a$ is more dominant than those of the spindle speed and depth of cut, as indicated in the previous statistical analyses. This is expected, since feed rate influences the mechanisms of chip formations, which largely determine the value of $R_a$. Deterioration of surface roughness at higher feed could be attributed to the increased strain rate of the composite material during machining. This promotes excessive fractures of the glass fibres and epoxy matrix; which results into a rougher surface or higher values of $R_a$. Apart from that, it is well understood from the theoretical surface roughness, in turning operation (using insert of certain tool radius), that $R_a$ can be given as [85, 182]:

$$R_a = \frac{f^2}{18\sqrt{3}R}, \quad \text{Eq. 4.4}$$

where $f$ is the feed rate, $R$ is the tool nose radius. However, it should be noted that this equation only provides a simple relationship of $R_a$, taken into consideration of only the feed rate, tool geometry and homogenous material during turning operation. In comparison, the values of $R_a$ during end milling can be affected by various factors, which can include the extent of tool wear, tool geometry such as tool concavity and relief angles [183], Figure 4.9, as well as the vibrations or chatter during machining [182]. In the case of FRP composites, $R_a$ value is also highly sensitive to the direction of measurement with respect to fibre orientation.
Figure 4.7: Effect of changing feed rate on surface roughness, $R_a$ at different spindle speeds
Figure 4.8: Effect of changing spindle speed on surface roughness, $R_a$ at different feed rates

- **$f = 500 \text{ mm/min}$**

- **$f = 750 \text{ mm/min}$**

- **$f = 1000 \text{ mm/min}$**
An increased spindle speed preserves the machined surface due to the reduction in material deformation at the tool-chip interface during the cutting process. Hence, surface finish is fairly improved with a higher spindle speed. However, the spindle speed should be controlled at an optimised level in order to alleviate the effect of wear on the cutting tool when machining these highly abrasive GFRP composites. Results of this surface roughness study appear to be comparable to those reported in literature, particularly for turning operation [5, 6, 9-12]. In spite of this, it is worth to highlight that as previously reported by Bhattacharyya et al. with Kevlar® machining [16, 17], $R_a$ values may not always clearly reflect the surface qualities of the machined composite parts. Particular care has to be taken when measuring surface roughness of the fibrous composite materials. There might be fibres and matrix fractures, fibre pull-out or fibre protrusions, delamination damage and matrix failure; all of which could lead to the large variations in the $R_a$ readings.

The aforementioned matrix and fibre failures after machining could be closely related to the cutting mechanism during machining. According to one of the cutting mechanisms explained in the literature for orthogonal machining of FRP composites, the fibre reinforcements are subjected to micro-buckling and bending failures as cutting progresses along the fibre direction (orientation of 0°), Figure 4.10 (a) [171]. It can be seen that surface below the tool edge is being compressed, which results into failures of fibre and matrix due to interfacial fracture [173]. When observing the cutting mechanism of each flutes individually, the rotating motion of the tool leads to the compression induced fractures perpendicular to the fibres. The sharp and brittle
fractures of the fibres indicate these failure modes, as shown by the arrows in the scanning electron microscopic images of the machined surfaces, Figure 4.11. On the other hand, arrows in Figure 4.12 depict the evidence of fibre protrusions and pullout from machined surface due to fibre debonding or failure of the polymer matrix. This is likely to be due to the reduction in tool sharpness, in which the tool no longer cuts the fibres cleanly. The presence of loose fibres on the machined surface affects the movement of stylus tip of the surface roughness measurer. This leads to large variations of $R_a$ readings as shown earlier, Figures 4.7 – 4.8.

Figure 4.10: Cutting mechanism of FRP composites [3, 111, 120]

Figure 4.11: SEM images of fractured fibres on the milled surface for the machining parameters of (a) $A_1B_1C_1$ and (b) $A_3B_3C_1$
As far as machining force, $F_m$, is concerned, it has been shown that the depth of cut is an equally dominant parameter which influences the $F_m$ during end milling of GFRP composites apart from the feed rate. This may be attributed by the fact that both feed rate and depth of cut determine the area of undeformed chip thickness [85], and specifically for GFRP composites, the number of fibre layers to be cut. This can be visualised using the orthogonal chip formation diagram, Figure 4.13. The area of undeformed chip is $A_c$, where $f$ can be interpreted as feed rate, and the width of cut, $b$ is the depth of cut.
Any changes of these parameters can significantly influence the magnitude of force experienced by the cutting tool during machining. Although the chip formation model depicted in Figure 4.13 is described for orthogonal machining, it can be applied for oblique cutting mechanics, such as milling and drilling, taking into consideration the different tool nomenclature. On the other hand, when machining of brittle material such as GFRP composites, fracture of glass and epoxy matrix reduces the tool/chip contact on the flank and rake faces of the tool. This tends to reduce the friction between tool and the workpiece material, which results in lower machining forces as compared to that of homogenous and ductile material, such as metals.

A gentle increase in the $S/N$ value of $F_m$, Figure 4.5, indicates a minor effect of spindle speed has on $F_m$, (with regard to decreasing machining force with higher spindle speed). This seems contradict the common perception. However, this could be justified by the fact that the increase in spindle speed generates higher friction work which elevates the cutting zone temperatures. As a result of low thermal conductivities of glass fibre and epoxy matrix, this tends to soften the polymer matrix and require less force to cut the material. Similar observations were reported by Wang et al. during orthogonal cutting of graphite epoxy composites [101]. Likewise, Lee et al. also demonstrated a reduction of machining forces with the increase in cutting speed during turning of GFRP composites [98].

Finally, with regard to tool wear and tool life, TL, it appears that the governing factor for TL is feed rate, which is rather contrary to other results [181] and the Taylor’s model. It is believed that the effects of cutting edge rounding and chipping observed in the lower ranges of machining parameters (level 1 in either of the machining parameters) hinder an accurate measurement of tool flank wear, Figure 4.14. The rounding of cutting edges arises due to abrasive, bending and spring-back actions of the E-glass fibres on cutting tool edges at the tool–fibre interface [76]. It is also worth arguing that the experimental range tested in this experiment may not be sufficiently discriminative to show any dominant effect of spindle speed on TL.

It is expected that the change in feed rate results in a higher heat energy being absorbed by the cutting tool to accelerate the tool wear as compared to that of spindle speed. In
contrast, the range of feed rate tested herein is in terms of table feed speed (in mm/min) instead of tool feed rate (mm/rev or mm/tooth). Consequently, the tool life during end milling is more likely to be influenced by this parameter instead of the rotational speed or spindle speed. On the basis of the aforesaid discussion, further investigations in the forthcoming study which incorporate a wider range and different domain of machining parameters is essential.

The dominant tool wear mechanism during machining of GFRP composites within the tested parameters is expectedly abrasion on the flank face of the cutting tool. Figure 4.15 (a) illustrates the contact and rubbing actions of the highly abrasive fibres on each cutting flutes with changes in the chip thickness. As apparent, the chip thickness is the smallest as the cutting tool initially engages the workpiece material; and the highest as the cutting flute is at the centre of the cutting (denoted by the circle, Figure 4.15 (a)). At this position, the cutting flute is fracturing orthogonally across the fibre, as illustrated in Figure 4.15 (b). This leads to a direct rubbing of the abrasive fibres on the tool flank face to rapidly wear out the tool material. Although the chip thickness reduces as the cutting flute gradually exits the workpiece material, each cutting flute maintains the same amount of contacts (as during the tool entrance) with the subsequent fractured fibres.

These two-body abrasions or rubbing actions of the fibres at the contact point of the tool result in the scratch marks on the tool flank face. This process is demonstrated by the
presence of smooth scratches on the flank surface of the cutting tool, as depicted in Figure 4.16 (a-b). Additionally, the impact from fibres generates dynamic stresses on the tungsten carbide (WC) hard grains and cobalt binder of the cutting tool, which leads to crack initiation and shedding or flaking of the grains [65]. This is evident in the higher magnification microstructure of the new/fresh tool surface and the worn tool surface shown side by side in Figure 4.16 (c-d).

![Figure 4.15: Contact and rubbing actions between the fibres and each cutting flutes (a) as the tool rotates and cuts across the fibres at the centre position and (b) close up view of central position [173]](image)

It appears that the WC grains are closely bonded together with the cobalt binder, Figure 4.16 (c), prior to machining test. As the tool wears out, voids on the worn tool surface are clearly visible as pointed-out by the arrows, Figure 4.16 (d). These microstructure characteristics indicate that the cobalt binders between the WC grains are severely removed by the highly abrasive fibre reinforcements. As the machining progressed, the fractured fibres can penetrate between the WC grains under high machining pressure to further erode the cobalt binder and fracture the larger WC grains into smaller fragments, Figure 4.16 (d). It is vital to note that the wear mechanisms described here were previously observed during machining or turning of particleboard [184]. The cyclic stresses of intermittent cutting action during end milling as the tool encounters different phases of GFRP material has resulted into micro-chippings on some of the cutting flute edges, shown in the white coloured box in Figure 4.16 (b). It can also be seen that the wear of the tool exhibited edge rounding, as mentioned earlier, which results from the bending effects and rubbing actions of fibre reinforcements on the end of the cutting tool edge, Figure 4.16 (e).
Figure 4.16: SEM images showing tool wear mechanisms from the end milling tests at the respective machining parameters.
Since the combination of compression, fracturing and bending rupture with little plastic deformation is the main mechanism during cutting of GFRP composites, the absence of other forms of wear exists. In fact, crater wear on the tool rake face and formation of built up edge (BUE) on cutting edges as observed in metal cutting is unlikely to occur due to the aforesaid chip formation mechanism. During end milling, chips are mostly of discontinuous type and in particular, for GFRP composites, the chips are mostly in the form of dusts, Figure 4.17.

Previous studies suggested that, the chips were formed mainly by fracture as a result of bending, buckling and brittle failures of fibre and matrix material ahead of the tool tip [111, 173]. Closer examination on the chips reveals segments of fractured fibres and epoxy matrix, Figure 4.17 (b). This could be attributed to the increase in strain on the composite material with higher cutting speed, which accelerates brittle fracture or behaviour of the epoxy matrix and glass fibres. Hence, this phenomenon could also be accounted for the reduction of machining forces during milling as the spindle speed is elevated, as discussed earlier.

As it is evident that the chips are discontinuous and short in nature, the ploughing on the tool rake face by those chips to form crater wear did not take place. Large amount sediments or remnants of charred thermosetting epoxy resin can also be seen on the flank and rake face of the cutting flutes, Figure 4.16 (f). This is due to temperature increase in the cutting zone which results from the low thermal conductivities of both epoxy resin and the glass fibres. Energy dispersive X-Ray spectroscopy (EDS) analysis performed at one of the positions on the tool rake face (see X in Figure 4.16 (f)) confirmed the adhesion of carbon (due to charred epoxy), Figure 4.18.

From these discussions, it can be established that the primary wear mechanism during machining of GFRP composites with the uncoated end mill tool is primarily due to mechanical abrasion by the fibre reinforcements with minor micro-chipping and cutting edge rounding. It is to note that the uncoated carbide tool exhibited acceptable range of tool life when compared to those reported in the literature during turning operation of the same material. The effects of fibre orientations or fibre angles (with respect tool/table feed direction) on tool wear are discussed in Chapter 5, in which wider and
different domains of machining parameters are employed. This will further clarify the incongruous result of tool life due to changing machining parameters.

Figure 4.17: SEM images of chip characteristics from the end milling test

Figure 4.18: Example of EDS analysis on the rake face of end mill tool (X is location of EDS scan, see Figure 4.16 (f))
4.4 Validation Test of Desirable Settings

A validation experiment was performed to confirm the desirable settings suggested from the Taguchi analyses discussed in the previous section. This experiment was carried out at the conditions not covered under the L9 Taguchi array, which is at the setting of A1B3C1 (f = 500 mm/min, s = 5,000 RPM, d = 1 mm). The results of validation experiment with their corresponding S/N ratios are shown in Table 4.11, whereas the following expression is used to estimate each of the machining outputs at desirable setting, \( \hat{\eta} \) [185]:

\[
\hat{\eta} = \eta_m + \sum_{i=1}^{q} (\eta - \eta_m)
\]

Eq. 4.5

\( \hat{\eta} \) is the mean of S/N ratio at the desirable level, \( \eta_m \) is the total mean of S/N ratio and \( q \) is the number of the experimental parameters employed in the Taguchi L9 experiment. It is to note here that the parameters given in Eq. 4.5 are determined for each of the machinability outputs considered herein. Using the experimental results given in Table 4.3 and Eq. 4.5, the average experimental values and their corresponding S/N ratios at the desirable parameter settings were calculated.

Table 4.12 exhibits the results of estimated outputs and experimental data at desirable settings of A1B3C1.

<table>
<thead>
<tr>
<th>Table 4.11: Results of validation experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experimental results</strong></td>
</tr>
<tr>
<td>Level</td>
</tr>
<tr>
<td>Force (N)</td>
</tr>
<tr>
<td>( R_a ) (( \mu m ))</td>
</tr>
<tr>
<td>TL (s)</td>
</tr>
</tbody>
</table>
Referring to Table 4.12, the evidence is highly conclusive that experimental values of the desirable settings are remarkably close to the calculated results, particularly for machining forces, $F_m$ and tool life, $TL$. However, due to variations in the $R_a$ readings, as discussed in the earlier section, it results in a higher percentage error between estimated and experimental values of $R_a$ at the desirable settings. SEM photos of the machined surface for validation experiments, Figure 4.19, confirmed this result that shows evidence of debris of fractured epoxies and fibres on the machined surface which influence and give large variations in the $R_a$ readings.

This validation experiment has demonstrated that the parametric study using Taguchi fractional DOE can provide a quick and reliable approach to analyse the parametric effects of experimental factors. Subsequently, Taguchi method allows determination of desirable parameter settings for maximising or minimising the machinability response during end milling of GFRP composites.
4.5 Concluding Remarks

This chapter has presented and discussed the parametric investigations of machinability for the GFRP composites during end milling using Taguchi’s design of experiment method. The following conclusions can be drawn based on results of the present work:

- Feed rate has the most dominant role in influencing surface roughness, $R_a$, followed by spindle speed, with each factor contributing 67% and 19%, respectively. The dominant effect of feed rate on $R_a$ may be attributed to different mechanisms of chip formation at various levels of feed rates. The effect of depth of cut was found to be negligible.

- It is worth noting that $R_a$ values alone may not be sufficient to describe the surface finish of GFRP composites. The presence of fibre protrusion, delamination, fibre bending and sub-surface damage on the machined part, as exhibited in the SEM images, may lead to the variations of $R_a$ readings.

- The resultant machining force, $F_m$ was significantly affected by feed rate and depth of cut at 54% and 45% contributions, respectively. This is because both parameters determine the cross-sectional area of the undeformed chip. Spindle speed was found to show marginal effect on the $F_m$.

- The tool life performance of the end mill cutter was mainly influenced by the feed rate (85% contribution) and spindle speed (11% contribution).

- It is believed that the effects of cutting edge rounding and chipping observed in the
lower range of machining parameters range may hinder accurate measurement of tool flank wear and eventually the tool life.

- The experimental range tested in this experiment may not be sufficiently discriminative to show any dominant effect of spindle speed on the tool life as to that of feed rate.

- The anomaly of this tool life results will be further investigated in the next chapter. Nonetheless, similar to that of $R_a$, influence of depth of cut on tool tool wear was insignificant.

- The predominant tool wear mechanism is mechanical abrasions on the flank face of the cutting tool. It has been discussed that 2 body micro-abrasion leads to further removal of cobalt binder and fracture of larger WC grains of the cutting tool into smaller fragments.

- It is necessary to highlight that selection for preferable parameters should depend on the end usage or the final machining requirement as the cutting parameters that produce lower tool wear or highest tool life, TL, do not give the highest production rate as well as improvement on $R_a$. 
Chapter 5 Regression Analyses of Tool Performance

5.1 Introduction

Findings presented in the previous chapter, Chapter 4, have shed some light on the parametric effects of different machining parameters on key machinability outputs during end milling of GFRP composites. However, ambiguous results on the tool performance (tool life) warrant further elaborate study. Thus, a series of full factorial experiments are properly designed and systematically planned to investigate this anomaly. Apart from that, these experiments are also planned to achieve the second objective of this thesis, which is to develop the tool wear predictive models during end milling of these composite materials. Outcomes of machining experiments herein are presented in two main sections.

The first section describes the machining performance of the tungsten carbide tool under a wide spectrum of machining parameters. Additionally, the machinability study of GFRP composites with different fibre orientations under similar machining parameters are carried out and presented. The Taylor’s tool life equations are subsequently employed to describe the relationships between the different experimental parameters. The second section of this chapter highlights the results of tool wear-machining force empirical relationships developed from multiple regression analyses. It demonstrates the pursuit for an indirect condition monitoring on the extent of tool wear using the measured machining forces, particularly, using the most important machining parameters.
5.2 Experimental Parameters

It is well understood that secondary finishing steps for composite materials such as machining is essential in order to meet the final product's dimensional control and functional geometric requirements. Despite being one of the widely employed machining processes in industry, research studies on end milling GFRP composites have not yet received its full due attention among research communities worldwide. As discussed in the earlier chapters, only a handful of researchers have reported experimental results on limited aspects of GFRP’s end milling machinability indices [113-116]. However, the various aspects of developing general and accurate tool life or tool wear prediction models for this machining process are hardly mentioned in the currently available literature.

As highlighted in the earlier chapters, this is mainly attributed to the complexity associated with the cutting actions in milling operation. Notably, due to multiple cutting edges, the cutting mechanisms change with different fibre orientations and/or architecture. The intermittent cutting mechanisms of the milling operation also lead to variations of chip sizes, contact stresses and cyclic temperatures. As a consequence, under certain machining parameters, the fluctuated loadings on the cutting edges may easily change the tool wear mechanism from that of continuous machining. Hence, the physical and mathematical descriptions of tool wear during end milling of GFRP composites still remains a challenge.

The limiting factor for consistent machining quality of GFRP composites is often due to the rapid wear of the cutting tools, caused by the highly abrasive fibre reinforcements [75, 186, 187]. During machining of GFRP composites, low thermal conductivities of both matrix material and the glass fibres may result in a higher temperature in the cutting zone. This, in turn, accelerates the wear of the cutting tool. Inadequate sharpness of the cutting tools lead to several surface quality problems, which include delamination damage, sub-surface damage, fibre pull-out or protrusions, and matrix and fibre fragmentation. Very often, poorly machined composite products degrade their in-service or mechanical performance and under the worst circumstances, cause them rejected prior to the end applications.
The complexity of machining process makes it impractical to predict the tool life or monitor the growth of tool wear for a single or specific machining parameter. A more practical way to predict or monitor the tool condition is by establishing physical or mathematical relationships under a range of machining parameters. Such relationship or model typically used in machinability studies is the traditional Taylor’s tool life equation [85, 188, 189]. The equation is given by:

\[ TL^{n_1} f_r^{n_2} a_p^{n_3} = C \]  

Eq. 5.1

where TL is the tool life (min), \( v \) is the cutting speed (m/min), \( f_r \) is the feed rate (mm/rev) and \( a_p \) (mm) is the depth of cut, while \( C, n_1, n_2 \) and \( n_3 \) are constants or exponents of the empirical relationship. In order to establish accurate and reliable tool wear/life models during end milling of GFRP composites, a series of experiments were carried out over a wide spectrum of machining parameters. The selection of machining parameters’ range was based on results from preliminary experiments as well as from previously published work [190].

These parameters were also set such that they covered the practice range of industrial applications and were within the limit of the CNC machine. Summaries of the machining parameters employed are displayed in Table 5.1. The axial depth of cut was kept constant at 2 mm as this parameter is known to be less important towards tool wear or tool life [80, 81, 190]. This depth of cut was chosen for a decent material removal rate to maintain uniform flank wear growth as well as to facilitate the morphological study of the machined surface through SEM.

<table>
<thead>
<tr>
<th>Machining parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindle speed, ( s )</td>
<td>3,000; 4,000; 5,000; 6,000 RPM</td>
</tr>
<tr>
<td>Effective linear cutting speed, ( v )</td>
<td>110, 150, 190, 230 m/min</td>
</tr>
<tr>
<td>Feed per tooth, ( f_r )</td>
<td>0.04, 0.06, 0.08 mm/z</td>
</tr>
<tr>
<td>Feed rate, ( f_r )</td>
<td>0.16, 0.24, 0.32 mm/rev</td>
</tr>
<tr>
<td>Fibre orientation, ( A )</td>
<td>0°, 90°</td>
</tr>
</tbody>
</table>
Similar to Chapter 4, machining experiments were performed in dry conditions or without any coolant or lubrication. This is due to the fact that previous study has not shown any benefits of using coolant or lubricant during machining of FRP composites [112]. Meanwhile, it is well known from orthogonal cutting of FRP composites that fibre orientations or fibre angles can largely influence the machinability of GFRP composites. Hence, machining and tool performance evaluations were carried out in two fibre orientations, e.g. along and across the fibre orientations of within the selected machining parameters. The fibre orientation, $A$, is designated as $0^\circ$ when the table or tool feed is along the fibre orientation, and $90^\circ$ when across the fibre orientation, Figure 5.1. It is essential to note that all of the fibre layers were carefully stacked in the same fibre orientation of $0^\circ$ or $90^\circ$ with respect to the tool feed or table feed direction during the composite fabrication. These two fibre orientations represent the extreme cases as far as the tool wear growth is concerned, based on the preliminary experiments conducted previously (refer to Appendix 5-1 for plots of the tool wear growth).

The Kistler® piezoelectric milling dynamometer (9265B), Figure 3.13, with charge amplifier (Kistler® 5001) was used to monitor the feed force, $F_x$, and the cutting force $F_y$, generated during each end milling pass, as explained in Chapter 3. Although the thrust force, $F_z$, was acquired during the end milling tests, it was not used in the analysis as it has no significant influence on the extent of tool wear [191]. The results of this study have shown that the trend of $F_z$ remains constant or plateau with respect to machining time in compared to that of tool wear.
5.3 Results and Discussion

5.3.1 Results of tool wear growth

(A) Effect of machining parameters on tool wear growth

Similar to previously discuss results in Chapter 4 and reported by other researchers [75, 80, 186, 187, 190], the tool wear or failure mechanism observed in this set of experiments is also predominantly due to abrasion on the flank face of each cutting flute. It is apparent that two-body abrasion between the fibres and the tool flank face resulted in the uniform scratch marks parallel to the tool rotation or cutting direction. This is depicted in the SEM micrographs, Figure 5.2 (a-b), in which it is noticeable that the parallel marks caused by rubbing actions of the fibres on flank face of the tool in the direction of tool rotation (indicated by the arrow). This can be verified by comparing with the condition of the fresh cutting edge on a new tool, shown in Figure 3.22.

The rubbing action of the fibres also further facilitated the rounding of the cutting edges due to the elastic spring back of the fibre [3], denoted by the oval in Figure 5.2 (c). The intermittent end milling cutting process and high fluctuation of machining forces when machining this composite material promote some micro-chipping on the edges of the cutting tool, as indicated by the white circle in Figure 5.2 (d). Details of tool wear mechanisms during machining GFRP composites have also been discussed in Chapter 4. It is to note that SEM micrographs of the worn tool for the other machining and fibre orientation parameters are given in Appendix 5-2. These micrographs clearly show the tool wear mechanisms discussed earlier.

The extent of tool wear was determined based on the average of three measurements of flank wear heights, $VB$, on all cutting flutes. The procedure for tool wear measurement described in Chapter 3 has been employed herein. Figure 5.3 displays the effects of changing cutting speed on the extent of tool wear with respect to machining time when the GFRP composites is machined for a constant feed rate. It can be noticed that the end mill tool was worn rapidly with the increase in cutting speed for each of the feed rates tested. When the cutting speed was further increased, the tool wear showed similar rate of growth, particularly under the extreme feed rate employed, Figure 5.3 (c).
Regression Analyses of Tool Performance

This is likely attributed to the increase of heat energy absorbed by fibres and the tool with the increase of cutting speed and feed rate. At a higher cutting (rotational) speed, the frequencies at which the exposed abrasive fibres rub against the cutting tool flank face increases tremendously. This accelerates the two-body abrasion between the cuttin
Figure 5.3: Effects of changing cutting speed with constant feed rate of: (a) $f_r$ of 0.16 mm/rev, (b) $f_r$ of 0.24 mm/rev and (c) $f_r$ of 0.32 mm/rev on tool wear growth
tool and workpiece material and ultimately leads to the cutting tool failure. Expectedly, at the lowest cutting speed of 110 m/min, the end mill tool worn gradually to give longer tool life or machining time prior to reaching the predefined wear criterion, regardless of the feed rate tested. Meanwhile, Figure 5.4 exhibits the growth of tool wear with respect to changing feed rate for all of the cutting speeds tested. The effect of changing feed rate on the growth of tool wear appears to be marginal in all cases of cutting speed employed, except when the cutting speed, $v$, is at 110 m/min, Figure 5.4 (a). It is also highlighted that the rates of tool wear cannot be clearly distinguished with respect to changing feed rate, especially under the highest cutting speed of 230 m/min, Figure 5.4 (d).

Based on these results, it can be concluded that cutting speed exhibited prevalent influence compared to the feed rate as far as the tool wear is concerned. This will be further confirmed by developing the traditional Taylor’s equation using the estimated tool life, as discussed in section (C). It is imperative to emphasise that contrary to machining of metals, the cutting performance of GFRP composites is influenced by the variety of fibre reinforcements and the polymer matrices [75, 76, 103, 109, 186]. The next section presents the experimental results, as far as the tool wear is concerned, during end milling of GFRP composites under the two extreme fibre orientations within the employed machining parameters (given in Table 5.1).

(B) Effect of fibre orientations on tool wear growth and surface quality

Figure 5.5 shows the tool wear growth for two extreme parameters of cutting speed, $v$; fibre orientation, $A$, and feed rate, $f_r$, tested. In general, tool wear rate is higher with an increase of the cutting speed regardless of the fibre orientations, as expected from the Taylor’s model. Interestingly, it is evident that a mild flank wear growth is experienced when the tool was fed across the fibre orientation, $A = 90^\circ$ as compared to along the fibre orientation, $A = 0^\circ$, Figure 5.5 (a) and (b). This results in a longer machining time prior to reaching the critical tool wear criterion. It was not initially anticipated, although Hocheng et al. reported similar trends when machining CFRP composites [111], under relatively less harsh machining parameters compared to the ones employed herein.
Figure 5.4: Effects of changing feed rate with constant cutting speed of: (a) \(v\) of 110 m/min, (b) \(v\) of 150 m/min, (c) \(v\) of 190 m/min and (d) \(v\) of 230 m/min on tool wear growth.
Regression Analyses of Tool Performance

Figure 5.5: Effects of changing fibre orientation, \( A \) at different machining parameters of: (a) \( f_r \) of 0.16 mm/rev, (b) \( f_r \) of 0.32 mm/rev, (c) \( v \) of 150 m/min and (d) \( v \) of 230 m/min on tool wear growth
The difference in the growth rate of tool wear can most likely be attributed to the tool/fibre contact mechanism during machining, Figures 5.6 – 5.7. When the tool is fed along the fibre direction, increasingly intense contact and rubbing actions of the fractured fibres on each rotating cutting flute can be observed. This is apparent as the undeformed chip thickness changes from small at the entry position of cutting to its maximum at the centre of cutting, during a single rotation cycle of the cutting tool, Figure 5.6 (a). At the centre position of cutting (denoted by the circle in Figure 5.6 (b)), each of the cutting flutes fractures the fibres orthogonally, which results in the fractured fibres rubbing directly on the flank face of the tool to abrade the tool material.

As each of the cutting flutes continues the rotating motion from the centre position, it maintains the same amount/rate of contact with the subsequent fractured fibres. Since the tool is fully immersed into the workpiece material, the cutting mechanisms promote a similar rate of abrasion for each single rotation of the cutting tool. On the other hand, when the tool was fed across the fibres, Figure 5.7, maximum direct contact between the tool and the fibres is only at the entry and exit points of the workpiece material. At these positions, the undeformed chip thickness is the smallest, while the contact time between fractured fibres and the tool flank face is relatively short. Although the chip thickness or loading is the highest at the centre position of cutting (denoted by circle in Figure 5.7 (a)), each rotating cutting flute seems to be sliding along the fibres instead of fracturing them.
Figure 5.7: Tool-fibre interface/contact at the centre of the cutting when tool feed direction was across the fibre orientation, $x$

This is evident from the orthogonal cutting mechanism depicted in Figure 5.7 (b). Apparently, the fibres fail due to buckling and bending [111], which alleviate the direct rubbing of the fractured fibres on flank face of the cutting tool. On the basis of this, a lower rate of tool wear or longer time to arrive at the predefined tool life criterion, Figure 5.5, is observed. Meanwhile, the effects of increasing feed rates while machining at different fibre orientations on the tool wear growth are illustrated in Figure 5.5 (c-d). At a lower cutting speed and constant feed rate, the growth of tool wear is seen to be substantially increased with changing of the fibre orientation. On the other hand, the difference in tool wear growth is marginal when high cutting speeds and feed rates were employed, Figure 5.5 (d). It can also be noted that the difference is not so obvious due to the changing of feed rate and fibre orientation. This could be attributed to the combination of high cutting speeds and feed rates, which lead to rapid rubbing actions and high heat energy being absorbed by the fibres and the cutting tool to accelerate the tool wear.

Although the results of tool wear progression indicate that better machinability (with respect to longer tool life) can be achieved when machining across the fibre orientation, it is worth noting that other criteria such as machined surface quality (surface roughness, delamination damage, fibre pull-out) are of equal importance to evaluate the overall machinability performance. Indeed, the resulting surface quality when the machining was carried out at the two cases of fibre orientations ($0^\circ$ and $90^\circ$) are compared side-by-side in Figure 5.8. It appears that severe delamination and fibre burrs
(uncut fibres) on the top side of the milled surface have offset the superior tool life performance obtained when machining was performed at 90° fibre orientation. It was observed that the harsher cutting parameters do not seem to improve on the quality and quantity of the uncut fibres either.

This is consistent with the results from Hocheng et al. when milling CFRP composites using a single square insert [111]. This is due to the fact that during machining, the top fibre layers do not have the support to restrain them from being pushed or slipped by the progressing cutting tool. Conversely, the cut is clean with no fibre roots on the top side of the machined surface for the former case (machining along the fibre orientation), Figure 5.8 (a). This evidence suggests that better machinability (with regard to surface quality) can be achieved while machining along the fibre orientation, even though the rate of tool wear is relatively higher. Based on a recent study of end milling CFRP composites with PCD tool at relatively different machining parameters [119], as outlined earlier in Chapter 2, it is asserted that regardless of the speed, tool material, and its sharpness, there is a critical fibre cutting angle in which delamination and fibre overhangs still occur.

Therefore, it is highly recommended to use a back-support when cutting across the fibre orientation in order to cut the fibres cleanly. This is clearly shown in the trial tests
conducted using a back support (made of polycarbonate), Figure 5.9, which distinctively reveal that the uncut fibres and delamination damage were totally eliminated. In addition, as asserted by Bhattacharyya et al. [10], the introduction of a thin resin rich layer on the top laminate surface may also help alleviate this problem.

Since the tool wear was predominantly observed on the flank face of each cutting flute, therefore, the morphology and integrity of the machined wall surface gives a better representation of the quality of machining with respect to the tool condition. For the specified machining parameters, it is evident that at the initial stage of machining, less damage was seen on the walls of the milled surface, Figure 5.10 (a-b). This is attributed to the fact that the tool was still sharp.
As cutting progressed, the combined effects of reduced tool sharpness and heat generation during machining have caused severe damage on the milled surface, in which the tool no longer cuts the fibres cleanly. As a result, the fibres were being pushed aside by the tool cutting edges that cause fibre pull-out and matrix failures. These are apparent on the SEM micrographs for the considered cases of fibre orientation, Figure 5.11 (a-d).

Figure 5.11: SEM images of machined wall surface for different machining parameters and fibre orientations
(C) Taylor’s tool life models and discussion
It is well established to use the traditional Taylor’s equation as a representation of the relationship between tool life and one or more variables of the machining parameters, such as cutting speed, feed rate and depth of cut, Eq. 5.1. As indicated earlier, the depth of cut has been kept constant. The study has taken fibre orientation, \( A \), as an additional parameter to determine its effect on tool wear or tool life during end milling of GFRP composites. Therefore, the Taylor’s tool life function can be reformulated according to the following equation:

\[
TL = C A v^n f^m \quad \text{Eq. 5.2}
\]

The criterion used in determining the tool life while machining the GFRP composites is 0.3 mm average flank wear on the cutting flutes. Figures 5.12–5.13 depict the variations of tool life, with respect to changing cutting speeds, feed rates and fibre orientations. The values of tool life were estimated from the tool wear curves, Figures 5.3–5.5. It is clear that cutting speed has a more dominant effect on the useful life of the end mill cutter compared to the feed rate, Figure 5.12. With regard to the fibre orientation, as discussed earlier, the change in fibre orientation eases the tool wear, which eventually prolongs the tool life, Figure 5.13.

![Figure 5.12: Variations of TL with respect to changing cutting speeds, \( v \) and feed rates, \( f \)](image-url)
Since the Taylor’s tool life equation, \( Eq. \ 5.2 \), follows a power law relationship, it must be transformed into a linear form to solve for the empirical constants, \( C \), \( n_1 \), \( n_2 \) and \( n_3 \). In this case, logarithmic transformations have been performed on each side of \( Eq. \ 5.2 \) to give a linear model of the initial Taylor’s equation as:

\[
\log TL = C + n_1 \log v + n_2 \log f_r + n_3 \log A
\]

\( Eq. \ 5.3 \)

Regression analysis was performed in order to determine the constants and describe the relationships between the tool life, \( TL \) with the selected experimental parameters. This was carried out using Microsoft Excel® Data Analysis tool pack with a 95% confidence level for all of the analyses performed. Results from regression analyses have shown that the Taylor’s tool life equation, \( TL \), evaluated as a function of cutting speed, \( v \) and feed rate, \( f_r \) is given by:

\[
TL = 10^{0.729} \times v^{-0.161} \times f_r^{-0.422}, \quad R^2 = 0.969
\]

\( Eq. \ 5.4 \)

When fibre orientation, \( A \), is taken into account, the extended Taylor’s equation is given by:

\[
TL = 10^{0.351} \times v^{-0.722} \times f_r^{-0.251} \times A^{0.445}, \quad R^2 = 0.946
\]

\( Eq. \ 5.5 \)
It is to be noted here that (for the case in which fibre orientation, $A$, is considered), the values of cutting speed, feed rate, and fiber angle were normalised from 0.1 to 0.9 against the corresponding maximum values of the input. This implies that the fibre angles of $0^\circ$ and $90^\circ$ are not considered. Meanwhile, judging from the $R^2$ values of 0.969 and 0.946 for Eq. 5.4 and Eq. 5.5 respectively, it can be concluded that both equations can describe the experimental trend very well. It is to note that the complete regression outputs for these equations are shown in Table 1 and Table 2 of Appendix 5-3. Analyses of $F_{\text{value}}$ and its significance from each regression output reveal that the models are statistically significant. It is essential to highlight that the $F_{\text{value}}$ for Eq. 5.4 is 138 compared to $F_{\text{test}}$ of 4.26 (from Fisher table), whereas $F_{\text{value}}$ for Eq. 5.5 is 24 as to $F_{\text{test}}$ of 6.59, which justifies the 95% confidence level set earlier to develop the equations.

Results from these statistical analyses suggest that cutting speed has the dominant influence on the TL. This was based on the exponents of the Taylor's equation, Eq. 5.4, in which $n_1 > n_2$ and $n_1 > n_3$ (where $n_1$, $n_2$ and $n_3$ are the exponents for the cutting speed, feed rate and fibre orientation, respectively). The expected inverse relationship of cutting speed with tool life is in agreement with previously reported studies of drilling and milling of the CFRP composites [65, 112, 124]. The reciprocal values of the cutting speed exponents obtained for both equations are also within the range of values reported when machining metals [188]. This warrants it to conclude that tool life is principally or highly dependent on the cutting speed. The results have clarified the incongruent effect of cutting speed on the tool life obtained from the previous parametric analysis, as in Chapter 4.

Although the change of fibre orientation certainly affects the rate of tool wear, surprisingly, the resulting exponent of Eq. 5.5 indicates that the influence of fibre orientation on TL is marginal as compared to that of the cutting speed. This is despite the two fibre orientations studied here are the extremes as far as the tool wear growth is concerned. From the aforementioned discussion, the wear and critical life of the cutting tool during end milling of this composite material are mainly governed by mechanical actions of the tool rotation and table feed during machining. Indeed, the combinations of these parameters contribute to the aggressive rubbing of the highly abrasive fibres on flank face of the cutting tool. This results in a rapid increase of heat energy being
absorbed by the tool during machining to accelerate the wear, and consequently reduces the tool life.

The fibre orientation plays an opposite role in influencing the tool wear growth and determining the critical tool life. This is judged from the trend of tool wear curve and the sign of its Taylor's equation exponent. As apparent, the effect of changing fibre orientation on the GFRP composites is not large enough to offset the results of increasing machining parameters. On the other hand, due to the fact that milling is a highly complex machining process which involves oblique cutting mechanisms, fibre orientation, $A$, cannot be easily controlled because of minute changes of fibre-tool contact which takes place continuously during the engagement of the tool with the workpiece material. It is worthwhile to note that in a previous study, Kim et al. pointed out that the principle factor of tool wear during turning of CFRP composites was fibre orientation [76]. However, results herein show a different picture.

(D) Validation of the Taylor’s tool life model

The variations of predicted TL with the measured experimental data are displayed in Figure 5.14 for different cutting speeds and feed rates. The mean absolute percentage error (MAPE), between predicted values and experimental data, calculated according to Eq. 5.6, has been found to be within 15%. Appendix 5-4 shows supplementary results of the predicted TL with respect to the two fibre orientations.

$$\text{MAPE} = \frac{100}{N} \times \sum_{i=1}^{N} \left| \frac{y_{\text{exp}} - y_{\text{pred}}}{y_{\text{pred}}} \right|$$  

Eq. 5.6

More encouraging results are exhibited when additional tests under randomly selected machining parameters, Table 5.2, are performed to validate the empirical equations, Eqs. 5.4 – 5.5. Figure 5.15 shows the growth of tool wear from these two confirmations or validation experiments, Test_1 and Test_2 respectively. Referring to Figure 5.15 (a), experimental TL for Test_1 has been recorded to be 3.00 min, whereas, the calculated TL from Eq. 5.4 is 3.09 min. The calculated TL according to Eq. 5.5 for Test_2 is 3.24 min in comparison to 3.38 min obtained from experiment, Figure 5.15 (b). The resulting
percentage errors between the predicted values and experimental data of TL are 3.00% and 4.29%, for Test_1 and Test_2, respectively. Thus, the Taylor’s equations can be used with a reasonable accuracy to predict the useful life of end mill tool when machining the GFRP composites.

![Figure 5.14: Variations of predicted and experimental TL when end milling along the fibre direction at different cutting speed and feed rate](image)

**Table 5.2: Validation tests parameters**

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Cutting Speed (m/min)</th>
<th>Feed rate (mm/rev)</th>
<th>Fibre orientation (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test_1</td>
<td>170</td>
<td>0.24</td>
<td>0°</td>
</tr>
<tr>
<td>Test_2</td>
<td>190</td>
<td>0.24</td>
<td>45°</td>
</tr>
</tbody>
</table>

![Figure 5.15: Tool wear growth from validation experiments of: (a) Test_1 and (b) Test_2, respectively](image)
5.3.2 Variations of machining forces

(A) Effect of machining parameters on machining forces

Similar to the parametric study reported in Chapter 4, machining forces were also used to evaluate the machinability of GFRP composites in this chapter. Although it has been found previously that feed rate has a more pronounced effect on the machining forces [113, 114, 190], the result was based on a relatively short machining period. The reason for such a procedure is to alleviate the effects of tool wear on machining forces for the parametric analysis. Hence, it will be interesting to investigate the variations of machining forces with respect to the different tool conditions and sharpness as the machining progressed. As mentioned earlier, the feed force, $F_x$, and the cutting forces $F_y$, generated after each end milling pass were constantly monitored using the Kistler® force dynamometer, Figure 3.13, until the tool reached the critical tool life criterion.

The effects of changing cutting speed on machining forces with respect to machining time are displayed in Figure 5.16 for a mild feed rate, $f_r$, of 0.24 mm/rev. It is imperative to note that these results were based on milling along the fibre orientation, $A = 0^\circ$. From the plots, it appears that during the early stage of the cutting operation, the effect of changing cutting speed on the magnitude of both machining forces is not so distinctive. This could be explained by the fact that the tool was still sharp, which results in a small difference of machining force magnitude with varying cutting speeds. This is consistent with the parametric analysis reported earlier in Chapter 4.

![Figure 5.16: Variation of (a) feed force, $F_x$, and (b) cutting force, $F_y$, with machining time for feed rate, $f_r$, of 0.24 mm/rev](image-url)
As the cutting operation progressed, the effects of changing cutting speed are more distinct. It is evident that the rates of increase in machining forces were similar to those obtained for tool wear growth, Figure 5.3. This implies that changes in the tool sharpness at elevated cutting speeds contribute to the variations of both machining forces magnitude. As a matter of fact, further increase in the cutting speed (from 190 to 230 m/min) has made no substantial difference to the rate of increase in machining forces, Figure 5.16. This seems to be consistent with the results obtained for tool wear growth, Figures 5.3 – 5.5.

Combinations of high cutting speeds and high feed rates are believed to contribute to this phenomenon. As discussed earlier, the rapid rubbing actions and increase in heat energy being absorbed by the cutting tool accelerate the wear and the machining forces. It can be seen from Figure 5.16 that the magnitude of feed force, $F_x$, is relatively high compared to the cutting force, $F_y$, towards the end of the tool life. This could be attributed to the high compressive load exerted by the fibre reinforcement on the tool as it was fed along the $x$ or fibre direction. In contrast, the increased cutting speed and tool wear promote thermal softening of the matrix material, which reduces the magnitude of cutting force, $F_y$, as depicted in Figure 5.16 (b). Appendix 5-6 shows the remaining results of effects of changing cutting speed on the machining forces for different feed rates employed.

The outcomes showing the effects of changing feed rate under the two extreme cutting speeds (at $s = 110$ m/min and $s = 230$ m/min) are displayed in Figure 5.17 and Figure 5.18 respectively. These results clearly demonstrate a substantial increase in the magnitude of both machining forces when changing the feed rate from 0.16 mm/rev to 0.24 mm/rev, particularly for the lowest value of cutting speed, $v = 110$ m/min, Figure 5.17. As machining progressed and tool sharpness deteriorated, the effects of increasing feed rate are also highly evident for most of the cutting speeds employed.

The dominant effect of feed rate on machining forces has been well explained in Chapter 4. As discussed in that chapter, both feed rate and depth of cut have greater influence on the forces acting on the cutting tool due to mechanisms of chip formation during machining. Since the depth of cut was fixed, feed rate shows a more dominant
Regression Analyses of Tool Performance

influence. This also explained the reason for the cutting force, $F_y$, having a higher magnitude of force compared to that of feed force, $F_x$, in Figure 5.17. This could be likely due to the fact that as the tool engaged and rotated into the workpiece material, an increased chip thickness/size led to a significant rise in the force in the cutting direction - $y$, Figures 5.1. The combined effects of rapid tool wear and changes in feed rate accounted for a rapid increase in machining forces exerted on the tool as the machining operation progressed, Figure 5.18.

![Figure 5.17: Variations of (a) feed force, $F_x$, and (b) cutting forces, $F_y$, with respect to changing feed rate at constant cutting speed, $v$ of 110 m/min](image)

![Figure 5.18: Variations of (a) feed force, $F_x$, and (b) cutting forces, $F_y$, with respect to changing feed rate at constant cutting speed, $v$ of 230 m/min](image)

Despite the difference extents of influence the cutting speed and feed rate have on tool wear and machining forces, both of them are taken into consideration when
relationships between tool wear and the machining forces are developed later in this chapter. It should be noted that the results presented earlier were from the cases when machining along the fibre direction, \( A = 0^\circ \). Similar to that of tool wear, machining force evaluations during end milling of GFRP composites were also performed under different fibre orientations (e.g. along and across the fibre orientation). The results are discussed in the following section.

(B) Effect of fibre orientations on machining forces

Due to the anisotropic nature of GFRP composites, distinctly different cutting mechanisms can be observed when machining at various fibre orientations with respect to the motion of the tool [111, 186]. This often leads to variations in machining forces. Research studies into prediction of machining forces with respect to fibre orientations, particularly during orthogonal machining, have been well described by several authors [9, 103, 104, 109, 192, 193]. As far as milling is concerned, Kalla et al. developed machining force prediction models during machining of CFRP composites at different fibre orientations [117]. Despite this, the models purely neglected the effect of tool wear during machining, in which their experiments were performed at a relatively low range of machining parameters with a shorter machining length or period.

Concerning this, results presented highlight the variations of machining forces at two fibre orientations, taking into consideration the changes in tool sharpness. The results herein show that similar to tool wear, variations in both feed and cutting forces are relatively smaller when the fibre orientation was at 90\(^\circ\) as compared to 0\(^\circ\) regardless of cutting speed or feed rate employed, Figure 5.19 and Figure 5.20. This could be attributed to the rate of tool wear growth discussed earlier.

Referring to these figures, even at the start of the machining operation (when the tool is still sharp) the difference in both machining force magnitudes is substantially higher when cutting at the two fibre orientations. It will be interesting as well as providing a clearer indication, if these are analysed and discussed. As depicted in Figure 5.21, these results indicate that lower machining forces were observed when the tool/table feed was at 90\(^\circ\) to the fibre orientation. Although the cutting tool was fed along or perpendicular to the fibre orientation, actual cutting action occurred as the cutting flute engaged into
the workpiece material, Figures 5.6 – 5.7. As evident, chip loading is highest at the centre of the cutting. The cutting mechanism at the centre of the chip formation can be well represented using the traditional orthogonal cutting model, Figure 5.22, which can be used to explain the results of machining forces magnitude shown in Figure 5.21.

Figure 5.19: Variations of (a) feed force, $F_x$, and (b) cutting forces, $F_y$, with respect to changing cutting speed and fibre orientation at constant feed rate, $f_r$ of 0.16 mm/rev

Figure 5.20: Variations of (a) feed force, $F_x$, and (b) cutting forces, $F_y$, with respect to changing cutting speed and fibre orientation at constant feed rate, $f_r$ of 0.32 mm/rev
Figure 5.21: Comparison of machining forces magnitude at two fibre orientations (sharp tool)

Figure 5.22: Chip formation mechanism during orthogonal cutting of FRP composites [3, 111, 120]
Results of machining forces in relation to chip formation and changes in fibre orientation during orthogonal cutting of FRP composites have been discussed in details elsewhere. Bending and buckling failures of the fibres [3, 111, 120] as the cutting flutes slide along the fibre, Figure 5.22 (a), contributed towards the lower magnitude of machining forces shown in Figure 5.21. This is the case when the tool was fed perpendicular to fibre orientation during the end milling operation. In the case of cutting across the fibre (tool fed direction is along the fibre orientation in end milling), Figure 5.22 (b), crushing-dominated fibre failure is more pronounced, which results in a lower magnitude of machining force [120]. However, direct contact of the tool flank face on the fibre reinforcement during cutting promotes high friction wear. As a result, this elevates the machining forces considerably.

5.4 Force Dependent Flank Wear Relationships

This section primarily aims to discuss the statistical modelling of tool wear for condition monitoring during end milling of GFRP composites. For any machining operation, continuous monitoring of the tool condition such as tool wear is imperative in determining a suitable time for tool replacement or re-conditioning. This is mainly to alleviate any adverse effects of the worn tool on the machined surface. As mentioned in Chapter 2, it has been well established in metal cutting that the techniques for tool condition monitoring during machining operations can be classified into the direct or indirect approaches. The common practice for monitoring the tool condition is by directly measuring the size of wear lands on the tool flank or rake faces. Nonetheless, this requires interruptions in the cutting operations which would demote machining productivity due to unscheduled downtime.

An indirect approach of tool condition monitoring that involve the development of empirical relationships between tool wear and the control variables (e.g. machining parameters and measured machining data) for online or real-time supervision offers a more practical solution for industrial applications. Methods based on measurements of tool forces, power, vibration and acoustic emissions have been attempted in several past studies particularly for metal cutting [133, 146, 147].
A review of the literature reveals that there is a limited number of published results with regard to tool wear monitoring during machining of composite material. Earlier, Lin et al. developed multiple regression and neural network models for tool wear monitoring during turning of aluminium silicon carbide MMC(s) [134]. Apart from this study, the currently available literature, particularly on machining of FRP composites, put more emphasis on the effects of processing parameters, tool and material properties on the machinability output. Previous studies also have included investigations of the machining induced damage on the FRP composites.

However, modelling of end milling GFRP composites, especially for tool wear, has hardly been discussed. The results presented earlier in this chapter have shown the evidence of steady growth of tool flank wear with machining time for different machining parameters and fibre orientations employed. It can be noticed that the tool wear growth also accounts for the variations of machining forces during cutting operations, Figure 5.23.

Similarities in the tool wear growth and machining force variations suggest that the measurement of machining forces during the cutting process can be used as an ‘indirect method’ to indicate the extent of tool wear. This is only true if a proper relationship can be established between these two parameters [19]. In addition, it may be expected that signals from machining forces are stochastic, particularly when dealing with highly anisotropic and non-homogeneous materials such as the GFRP composites. Therefore, the monitoring and estimation schemes must be designed to take into account such variations that might exist [135].
Figure 5.23: Tool wear growth and variation of (a) feed force, $F_x$, and (b) cutting force, $F_y$. "Cutting Speed, $v$" and "Feed Rate, $f_r$" are provided in the table below:

<table>
<thead>
<tr>
<th>Cutting Speed, $v$ (m/min)</th>
<th>110</th>
<th>150</th>
<th>190</th>
<th>230</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed Rate, $f_r$ (mm/rev)</td>
<td>0.24</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tool Wear Force

- Tool Wear
  - 110 m/min: ●
  - 150 m/min: ◆
  - 190 m/min: ▲
  - 230 m/min: ■

Cutting Force

- Force
  - 110 m/min: ○
  - 150 m/min: ◦
  - 190 m/min: △
  - 230 m/min: □
5.4.1 Simple regression of tool wear – machining force relationships

In the first stage of this statistical analysis, basic regression fittings were performed on individual machining parameters employed in order to understand the relationships between tool wear and the machining forces. Experimental data were fitted using linear and power law functions for feed force, $F_x$, and cutting force, $F_y$, as depicted in Figure 5.24 (a-b). From these individual analyses, it appears that the changes of tool wear with machining forces can be fairly accurately modelled using both functions. However, judging from the $R^2$ values for most of the regressive outputs (taken from different machining parameters), the power law function yields a more accurate result to match the experimental data, Figure 5.24.

![Figure 5.24](image-url)

**Figure 5.24:** Individual regression results for (a) feed force, $F_x$, and (b) cutting force, $F_y$, for the respective machining parameters
5.4.2 *Multiple regression of tool wear – machining force relationships*

The general tool wear-machining force relationships representing all machining parameters employed in this work were developed using multiple regression analysis (MRA). As previously discussed, fibre orientation was deemed to be less critical due to its relatively low influence on TL. This was based on the results of Taylor’s tool life equation, *Eq. 5.5*, shown earlier. As far as the machining composite material is concerned, cutting speed and feed rate are still the most governing parameters to influence the tool wear and tool life. Additionally, the SEM micrographs and the photos of the machined surface presented earlier show a poor result while machining at 90° fibre orientation. Because of these reasons, the fibre orientation has not been used as one of the input variables to develop the empirical models.

Since the aforesaid power law relationship of individual machining parameters gives a better approximation of tool wear, therefore, the force dependent flank wear relationships considering all of machining parameters can be represented as follows:

\[ TW = C v^\alpha f^\beta F^\gamma \]  

*Eq. 5.7*

where *TW* is the tool wear (mm), *C* is the empirical constant, *v* is the cutting speed (m/min), *f* is the feed rate (mm/rev), *F* is either feed or cutting force (N), while *α*, *β* and *γ* are the corresponding exponents of the empirical model.

Taking into account the feed and cutting forces separately, the general equations from MRA (when machining the GFRP composites at fibre orientation of 0° with respect to tool/table feed direction) are given by *Eqs. 5.8* and 5.9 respectively as:

\[ TW = 10^{-2.547} v^{-0.409} f_r^{-0.564} F_x^{1.150}, \quad R^2 = 0.851, \]  

*Eq. 5.8*

\[ TW = 10^{-3.382} v^{-0.694} f_r^{-1.296} F_y^{1.667}, \quad R^2 = 0.821, \]  

*Eq. 5.9*

Overall, judging from the values of *R*^2^, the results of these multiple regression analyses suggest that the general equations can predict the trend of tool wear with acceptable
accuracy. It is also evident that the tool wear-feed force equation gives a slightly better prediction on the extent of tool wear as compared to the tool wear-cutting force relationship. Owing to the nature of discontinuous or intermittent cutting actions during end milling as well as the random variations in material properties, high scattering or fluctuation of the measured cutting force data ($F_y$) is observed. This is obvious as the tool fractures the non-homogeneous layers of fibre reinforcements and epoxy matrix with different chip sizes. On the basis of these factors, slightly poorer results are obtained in the regression analysis, as given in Eq. 5.9.

Subsequently, Eqs. 5.8 and 5.9, were used to calculate the extent of tool wear based on the machining parameters employed and measured machining forces. The results are displayed in a similar manner for feed and cutting force respectively, as indicated in Figures 5.25 – 5.26. It can be seen that the experimental data being partially within the ±15% zone of the calculated values from both equations. However, the equations seem to underestimate the extent of tool wear within a certain range of machining parameters and machining force region. This is likely to be a result of the linear interpolative nature of the regression analysis, which results in a less accurate prediction under a particular combination of cutting parameters and measured machining forces.

Results from these statistical analyses were based on the 95% confidence level set earlier during regression analyses. Details of regression outputs for the developed equations given in Appendix 5-7 are used to perform the test of significance for the regression models. The value of $F$-test (334.08) and its significance (< 0.05) in the ANOVA table, Table 3 (Appendix 5-7), for the model given in Eq. 5.8, show that the equation is statistically significant on the response, $TW$. Likewise, ANOVA results for the model in Eq. 5.9, as tabulated in Table 4 of Appendix 5-7, draw similar conclusions. On the other hand, normal probability plots of residuals shown in Appendix 5-8 confirmed the normality assumption of the measured data. As shown, the points are well spread along but closely to the straight line, which concludes that the experimental data were normally distributed.

Appendix 5-9 shows the supplementary results (for other parameter sets) of the MRA predicted tool wear in comparison to experimental data and the ±15% zone.
Figure 5.25: Comparison of experimental and predicted data from MRA at (a) $v$ of 150 m/min, $f_r$ of 0.16 mm/rev and (b) $v$ of 190 m/min, $f_r$ of 0.24 mm/rev
Regression Analyses of Tool Performance

Figure 5.26: Comparison of experimental and predicted data from MRA at (a) \( v \) of 150 m/min, \( f_r \) of 0.24 mm/rev and (b) \( v \) of 190 m/min, \( f_r \) of 0.24 mm/rev

The ratios of predicted values to the experimental data for each of the developed equations are presented using histograms in order to compare their statistical characteristics (based on frequency density functions). As shown in these
histograms, Figure 5.27, the standard deviations of the calculated ratio are 0.1836 and 0.1563 for cutting force, $F_y$, and feed force, $F_x$, equations respectively. This shows the tendency for the variance of the ratio to decrease with the shift from using cutting force data to feed force data in order to predict the tool wear. Hence, this supports the results of regression analysis presented earlier with regard to the accuracy of tool wear-feed force relationship.

Figure 5.27: Ratio of predicted values against experimental data for (a) feed force, $F_x$ and (b) cutting force, $F_y$
Scatter diagrams, Figure 5.28, were plotted to demonstrate the accuracy of the predicted tool wear from MRA equations in comparison to the experimental data under all experimental parameters. A perfect prediction would show that all data points lie on the 45° line. A ±15% error zone line is imposed along the 45° line to display how close the comparative data points are bunched together. Comparatively, there are a number of data points, scattered outside the error zone for both models, Figure 5.28. This indicates only adequate accuracy or agreement of the MRA capabilities in predicting the tool wear.

![Figure 5.28](image)

Figure 5.28: (a) Scatter diagram of MRA predicted values against experimental data for (a) feed force, $F_x$ and (b) cutting force, $F_y$

In the forth-coming chapter, results obtained from the fuzzy logic modelling are discussed and compared with the outputs obtained from the statistical models presented here. This will indicate the most effective model which can accurately predicts the extent of tool wear during machining of GFRP composites.
5.5 Concluding Remarks

This chapter has presented the results of tool performance evaluations during end milling of GFRP composites using the uncoated tungsten carbide tool. The experiments have been carried out under a wide spectrum of machining parameters and two different fibre orientations. The Taylor's equations have been employed to determine the useful life of the end mill cutter during machining of this composite material. Later on, the tool wear-machining force relationships have been developed as an indirect method of monitoring the cutting tool condition for different machining parameters. The following conclusions can be drawn from the results presented earlier:

- An increased cutting speed or feed rate accelerates the tool wear growth and leads to rapid failure of the cutting tool.
- Machining across the fibre orientation (90° to fibre orientation) eases the growth of the tool wear, which eventually prolongs the tool life when compared to machining along the fibre orientation (0°). The marginal increases of tool wear when machining at this fibre orientation (90°) are likely due to inherent tool-fibre contact.
- Results from the Taylor’s equations have confirmed that tool life of the end mill cutter is strongly influenced by combinations of cutting speed and feed rate.
- As indicated in the equations, the effect of machining at the two fibre orientations does not show significant or discriminative influence on the tool life as compared to those of varying machining parameters.
- The Taylor’s predicted tool life yields excellent accuracy with average percentage error to be within ±15%.
- The progression of tool wear can be effectively monitored without interrupting the cutting process by using the developed relationships between tool wear and machining forces. General equations from MRA (based on power law function) exhibit an acceptable accuracy in predicting the extent of tool wear when compared to the experimental data.
- The evidence is strongly conclusive that reasonably accurate tool wear prediction can be well achieved using the feed force, $F_x$, data rather than the cutting force, $F_y$, data.
Chapter 6 Fuzzy Logic Analyses for Tool Condition Monitoring

6.1 Introduction

Chapter 2 (Literature search) has earlier highlighted that soft computing modelling techniques, namely ANN and fuzzy logic modelling, have been widely employed in various research studies. In spite of the more implicit expression, they are favourable due to the ability to map experimental trends with a high degree of accuracy. As a matter of fact, a predictive model based on neural network and fuzzy logic often compensates for the limitations of the conventional statistical or regression model (which is derived through linear interpolation technique), in predicting a nonlinear and stochastic relationships between experimental parameters [159].

One of the main attractions of the soft computing approach is that it is not necessary to postulate a complex mathematical equation beforehand in order to model experimental relationships. Principally, the constitutive relationship of experimental parameters can be ‘learned’ by a neural network model through adequate training of experimental data. A fuzzy logic model, on the other hand, constructs the input-output mapping according to human thinking characteristics or decision rules using the stipulated input-output data pairs. Hitherto, a number of research studies have reported the successful applications of ANN and fuzzy logic techniques to model experimental relationships. These include the modelling of machinability output characteristics such as surface roughness, machining forces and tool wear during metal cutting [117, 144, 145, 149, 157, 194, 195].
Some results have been published with regard to the application of ANN to predict delamination damage, surface roughness, and machining forces during drilling, milling and turning of composite materials [55, 117, 160-162, 165, 166, 196]. However, the development of a tool wear predictive model (through fuzzy logic) for condition monitoring while end milling GFRP composites has yet been attempted in any past study. Results from the previous chapter (Chapter 5) have shown that empirical relationships of tool wear-machining forces can be adequately modelled using multiple regression analysis. Nevertheless, the anisotropic and non-homogeneous natures of GFRP composites as well as the stochastic behaviour of the machining operation are likely to cause large variations and noise in the machining force measurement. This results in a less accurate constitutive relationship of tool wear-machining forces (based on statistical approach) for any useful practical applications.

On the basis of this, as well as the results from literature [134, 145, 148, 149, 157, 194, 195], the applications of neural network and fuzzy logic modelling are expected to improve the prediction of tool wear. This chapter proposes the adaptive network-based fuzzy inference system (ANFIS), also known as Neuro-Fuzzy, as the predictive model to monitor the extent of tool wear during machining of GFRP composites. Experimental results from Chapter 5 that consist of tool wear machinability data obtained from a wide range of end milling experiments were used to develop the ANFIS predictive models.

It is imperative to highlight that, in spite of the currently available and various neural network models developed in past research on modeling of machinability indices, they suffer from several limitations. Among these are the localisation properties of the radial basis function (RBF) network, which results in a random selection of activation function centre and their spread [197-199]. Conversely, the multi-layer perceptron (MLP) network is highly sensitive to randomisation of input-output data pairs and the number of input parameters [156]. In view of this, fuzzy logic modelling coupled with neural network training, is proposed to overcome these limitations.

This chapter begins with the principles of a fuzzy logic or fuzzy inference system and its suitability. It is followed by a general discussion on the architecture and learning
algorithm of the ANFIS model. Subsequently, the development procedure and the results of the developed predictive models are presented along with their statistical performance. These results are compared with the experimental data and the results of MRA techniques presented in Chapter 5. Finally, the superiority of the developed ANFIS models is commented upon.

6.2 Prediction and Monitoring of Tool Wear using ANFIS Model

6.2.1 Background of Fuzzy Logic or Fuzzy Inference System

In 1965, Zadeh proposed the theory of fuzzy logic, also currently known as fuzzy inference system (FIS), as a solution for making decisions based on vague, ambiguous and imprecise data [156, 200]. Following that idea, Assilian and Mamdani reported the earliest implementation of fuzzy logic rules for a steam generator controller [156]. Nowadays, FIS has become one of the extensively used soft computing methods to model control and automation systems. Indeed, on the basis of its multidisciplinary nature, FIS has been attractive in other engineering applications. This includes the modelling of highly nonlinear input and output relationships in machining operations [144, 145, 157, 158, 194, 201].

FIS typically employs a human reasoning or human structured knowledge in the form of fuzzy rules to match a given input into a desired output. This is as opposed to the conventional method of using or developing complex mathematical models or equations. An FIS model normally consists of four modules or steps, namely: (a) input database, (b) fuzzy/rule base, (c) fuzzification, and (d) defuzzification, as depicted in Figure 6.1. The input database defines the fuzzy membership functions (MFs) to be implemented in the FIS. On the other hand, the rule base contains a selection of fuzzy rules and an inference engine, which are used to carry out fuzzy reasoning of the input MFs in order to produce the fuzzy outputs. Finally, the aforesaid defuzzification step provides the final crisp values of the FIS using the fuzzy output derived from the fuzzy inference engine.
It is essential to note here that the primary working mechanism of an FIS is through the construction of a set of fuzzy rules, which are in the form of IF-THEN statements. These rules or statements are evaluated in parallel, using fuzzy operators which facilitate the input and output matching. The commonly employed fuzzy operators (known as logical operators) for fuzzy inferencing are the AND, OR and NOT operators. An example of a basic fuzzy rule with the logic operator is as follows:

\[
\text{IF } I_1 \text{ is } N \text{ AND } I_2 \text{ is } A \text{ THEN } O \text{ is } AR.
\]

6.2.2 Architecture of ANFIS

ANFIS is an advanced FIS with the learning capability of a neural network. The learning feature distinctively differentiates it from the traditional FIS, as the neural network training or algorithm enables the change in the FIS structure and its parameters. Due to this fact, fine tuning of the predicted output would be possible [202]. The application of fuzzy inferencing, on the other hand, allows better interpretability of the neural network while maintaining the accuracy of the input-output mapping [203]. It reduces computational efforts, which typically be required in the neural network algorithm, such as in the MLP network [204].

Similar to that of any neural network model, working principles of ANFIS is based on its architecture. The architecture of ANFIS was initially proposed for a control system by Jang et al. [198, 199]. It provides the input-output mapping through the combination of ‘learning’ and ‘fine-tuning’ procedure of neural network training and fuzzy
inferencing. The term ‘adaptive’ implies that any part of functions in the ANFIS architecture or layer have parameters which influence the outputs of respective layer [198, 199]. ANFIS learning rules and fuzzy inferencing also specify how these parameters should be changed in order to minimise the error measure [198, 199].

Figure 6.2 exhibits the architecture of a simple ANFIS system that consists of two inputs ($x$ and $y$), each with 2 MFs, a fuzzy rule base ($R$ number of rules) and a single output, $f$. The network implements the first order (linear function) Takagi-Sugeno type fuzzy reasoning for learning and fine tuning. Examples of the first order Takagi-Sugeno fuzzy rules can be in the form of:

Rule 1: IF $x$ is $A_1$ AND $y$ is $B_1$ THEN $z$ is $f_1(x,y)$
where $f_1 = p_1 x + q_1 y + r_1$

Rule 2: IF $x$ is $A_2$ AND $y$ is $B_2$ THEN $z$ is $f_2(x,y)$
where $f_2 = p_2 x + q_2 y + r_2$

Figure 6.2: A simple two input-single output ANFIS architecture
The aforesaid fuzzy rules can be illustrated as in Figure 6.2 and Figure 6.3, where $x$ and $y$ represent the inputs, $f$ is the overall output from the architecture, and $A_1$, $A_2$, $B_1$, $B_2$ are the linear or nonlinear parameters or fuzzy sets of the MFs. These parameters are typically represented in terms of linguistic variables (words) of SMALL, MEDIUM or HIGH based on the selected MFs curves. On the other hand, the $p_1$, $p_2$, $q_1$, $q_2$, $r_1$ and $r_2$ are linear coefficients of the Takagi-Sugeno first order models, $f_1$ and $f_2$.

As depicted in Figure 6.2, the architecture of an ANFIS network comprises five distinct layers of feed-forward neural network. These layers are typically characterised by the operations that they perform, namely: (1) fuzzification; (2) fuzzy rule; (3) normalising; (4) defuzzification and (5) overall output. The architecture of each layer is represented by different node functions, which can be in the form of adaptive nodes (denoted with squares) and fixed nodes (denoted with circles). The parameter sets are adjustable in the square nodes, whereas they are fixed in the circle nodes. During fuzzy inferencing, the output signals from each layer are processed by the node functions in order to provide the input signals for the subsequent layer.
6.2.3 Processing of node functions in ANFIS architecture

The signal processing by node functions in each layer of the ANFIS architecture is briefly explained below, whereas greater details are available elsewhere in [198, 199]:

- Layer 1: Each node in this layer contains adaptive node functions, in which they are used to map or fuzzify the inputs, $x$ and $y$, into the corresponding fuzzy linguistic values of SMALL, MEDIUM or HIGH using fuzzy MFs. Fuzzified output, $O_i^1$ is given by:

$$O_i^1 = \mu A_i(x), i = 1, 2,$$

Eq. 6.1

where $\mu A_i(x)$ denotes the MFs of the corresponding linguistic values for the first input. In general, the MF can take the form of a linear function such as a triangular and trapezoidal function or a nonlinear function like a generalised bell shape, Gaussian or sigmoid function. Each of the MFs has parameters which depend on their respective curves (the selected MF is discussed in later section). Meanwhile, the corresponding linguistic values of the input are normally defined according to the range of the input parameter.

- Layer 2: In this layer, the fixed node function provides the strength for the layer 2 output signal rules, $O_i^2$, by multiplying each input signals from Layer 1 with one another. This is given by:

$$O_i^2 = \omega_i = \mu A_i(x) \times \mu B_i(x), i = 1, 2.$$

Eq. 6.2

where $\omega_i$ is the output signal from Layer 2 (also known as firing strength) and $\mu B_i(x)$ is the corresponding MFs linguistic values for the second input.

- Layer 3: This layer calculates the normalised firing strength of the fuzzy rules, $\overline{\omega_i}$, obtained from the previous layer. This is achieved through:

$$\overline{\omega_i} = \omega_i / \sum_{i=1}^{s} \omega_i, i = 1, 2.$$

Eq. 6.3
Layer 4: Defuzzification of the first order Takagi-Sugeno type fuzzy rules to solve the overall weighted output, $\bar{\omega}_i f_i$, using the normalised firing strength, $\bar{\omega}_i$, is performed in this layer. Typically, defuzzification is accomplished using the following expression:

$$\bar{\omega}_i f_i = \bar{\omega}_i (p, x + q, y + r), i = 1, 2.$$  

Eq. 6.4

Layer 5: Finally, the overall output is calculated using the sum of all weighted signals from layer 4. This is given by:

$$f = \bar{\omega}_1 f_1 + \bar{\omega}_2 f_2$$

$$= (\bar{\omega}_1 x) p_1 + (\bar{\omega}_1 y) q_1 + (\bar{\omega}_2 x) p_2 + (\bar{\omega}_2 y) q_2$$

Eq. 6.5

where $f_i$ and $f_2$ are the Takagi-Sugeno first order linear functions, $p_1, q_1, p_2, q_2$ are the linear coefficients of those functions.

6.2.4 Learning algorithm of ANFIS model

The ANFIS model applies the hybrid learning algorithms, Figure 6.4, of gradient descent and the least-squares estimation, in tuning the FIS parameters to match the training data [144, 157, 158, 194, 205]. Referring to Figure 6.4, it can be seen that starting from the forward pass of the neural network, function signals move forward until Layer 4 so that the consequent parameters can be optimised by the least-square estimation in order to determine the error rates [198, 199]. During the backward pass, error rates are propagated backward to update or fine-tune the MFs parameters by the gradient descent. The learning or training processes of gradient descent technique continue until the desired number of training iterations or epochs (which is decided based on the number of datasets) has been reached. Apart from this, the lowest root mean square error (RMSE) between the measured and the generated output is often used as the stopping criterion of the neural network training [194, 205].
6.2.5 ANFIS modelling procedure

(A) Construction of ANFIS model

Similar to that of MRA, two different ANFIS models were constructed using feed force, $F_x$, and cutting force, $F_y$, datasets in order to predict a single output variable, tool wear, $TW$. This approach offers the flexibility of having different types of MFs in the ANFIS architecture. Hence, the five-layers of ANFIS architecture in the current work consists of 3 inputs of cutting speed, $v$, feed rate, $f_r$, and machining forces (either $F_x$ or $F_y$) with the output variable $TW$ as indicated in Figure 6.5. The ANFIS models are denoted as $ANFIS_{F_x}$ and $ANFIS_{F_y}$ for feed force and cutting force datasets respectively. Prior to the ANFIS modelling, restructuring of the datasets was performed to enhance the predictive capability of the fuzzy model. Firstly, the feed and cutting force datasets were normalised to the values between 0.1 and 0.9 in order to produce uniform non-dimensional experimental data. This was carried out using the following expression:

$$x_a = 0.1 + 0.8 \times \left( \frac{d_i - d_{\min}}{d_{\max} - d_{\min}} \right)$$  \hspace{1cm} \text{Eq. 6.6}
where \( d_{\text{max}} \) and \( d_{\text{min}} \) are the maximum and minimum values of raw data while \( d_i \) is the \( i^{\text{th}} \) data point of a dataset.

Figure 6.5: The implemented ANFIS architecture

In order to achieve a generalisation of the ANFIS model, the normalised data were then divided into training and checking datasets, as would normally be performed in any neural network models. The training dataset was used to generate the fuzzy rules, train the neural network and fine tune the MFs of the ANFIS model. Machinability data and/or experimental results gathered from the wide range of experiments in Chapter 5 were used for training of the ANFIS models. The validation of the trained ANFIS models was then implemented using new input values from the repeated experiments under randomly selected machining parameters. Obviously, these new datasets were different from the training datasets.

Table 6.1 summarises the ranges of values for training and validation input-output datasets used to develop the ANFIS predictive models. It is necessary to note that these
datasets were also randomised prior to training and validation to improve the predictive capabilities of the ANFIS models.

Table 6.1: The range of input and output values used during ANFIS training and validation prior to normalisation

<table>
<thead>
<tr>
<th>Input/Output variables</th>
<th>Training data range</th>
<th>Validation data range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
<td>Minimum</td>
</tr>
<tr>
<td>Cutting speed, $v$ (m/min)</td>
<td>110</td>
<td>230</td>
</tr>
<tr>
<td>Feed rate, $f_r$ (mm/rev)</td>
<td>0.16</td>
<td>0.32</td>
</tr>
<tr>
<td>Feed force, $F_x$ (N)</td>
<td>25</td>
<td>230</td>
</tr>
<tr>
<td>Cutting Force, $F_y$ (N)</td>
<td>41</td>
<td>210</td>
</tr>
</tbody>
</table>

(B) **Selection of membership functions (MFs)**

An important element in the ANFIS modelling is the selection of parameters for fuzzy inferencing, which includes the type and number of MFs. These parameters are essential to form the fuzzy “if-then” rules. As outlined earlier in Section 6.2.2, the MFs can take the form of a linear function such as a triangular or trapezoidal function, or a nonlinear function such as generalised bell shaped, Gaussian or sigmoid functions. The developed ANFIS model has employed the nonlinear Gaussian MFs for each of the input data (cutting speed, feed rate and machining forces), Figure 6.6. The smoothness and symmetrical shape of the Gaussian functions make them suitable for the development of these highly nonlinear tool-wear machining force relationships. A Gaussian membership function is typically spreads across the experimental input range with the maximum and minimum degree of membership range from 0 to 1, which is given by:

$$
\mu A_j = \exp \left[ -\frac{(x_j - a_j)^2}{2b_j^2} \right] \quad Eq. 6.7
$$

where $x$ is the input parameter, and $a$ and $b$ are the Gaussian function parameters that need to be optimised in the input space partitioning stage (this will be discussed in the
subsequent section). Parameter $a$ represents the Gaussian function centre (mean), whereas $b$ determines the width (standard deviation) of the Gaussian function.

![Gaussian membership/activation function for ANFIS](image)

Figure 6.6: Gaussian membership/activation function for ANFIS

(C) Data and input space partitioning

Data and input space partitioning or clustering for the ANFIS model is crucial as it determines the number of fuzzy rules to be derived as well as the numbers and size of the MFs to be employed. The purpose of clustering is to identify the natural groupings of a large dataset so as to produce a concise representation of a system's behaviour [197]. A relatively straightforward, yet effective approach is to partition the input space through a grid partitioning. This method divides the input space into rectangular sub-spaces using axis paralleled partition based on a pre-defined number of MFs [206]. Figure 6.7 illustrates the typical grid partition of a two dimensional input space, $A$ and $B$, with each having three membership functions. It results in 9 fuzzy rules for this type of configuration. However, the main limitation of this type of data partitioning is that the number of fuzzy rules rises exponentially, when both number of input variables and pre-defined MFs increases. This problem, usually referred to as “the curse of dimensionality” [199, 206], would demand more computational efforts during fuzzy inferencing and neural network training.
Consequently, the input space partitioning of the training datasets was performed using the subtractive-clustering technique (initially proposed by Chiu [197]). This clustering technique determines the optimum numbers of Gaussian MFs and fuzzy rules required for the ANFIS model. It is predominantly useful when there is no clear indication on how many clusters that can be used for a given set of data [197]. This is particularly the case for the machining forces datasets employed in the current analysis. The subtractive-clustering assumes that each data point can be a potential cluster centre and calculates the likelihood of each selected point being the cluster centre [206]. A data point with the highest potential, which is a function of the distance measured between each data point, is then considered as a cluster centre. The potential of each data point is estimated by the following equation [207]:

$$P_i = \sum_{j=1}^{n} e^{-\alpha |x^j - x^i|^2}$$  \hspace{1cm} Eq. 6.8

where, $\alpha$ is given as:

$$\alpha = \frac{\lambda}{r_a^2}$$  \hspace{1cm} Eq. 6.9

$P_i$ is the potential of the $i^{th}$ data point, $n$ is the total number of data points, $x^j$ and $x^i$ are data vectors in data space, including both input and output dimensions, $\lambda$ is a positive constant and $r_a$ is known as the hypersphere cluster in the data space or simply the ‘cluster centre’. A large value of $r_a$ results in fewer clusters which lead to a coarse
model, whereas, a small value of $r_a$ produces an excessive number of rules which may results in an over-defined system. Subtractive-clustering has additional three parameters, namely the accept ratio ($\varepsilon$), reject ratio ($\bar{\varepsilon}$) and quash factor ($\eta$) which need to be specified or defined [207].

These parameters, particularly the $\varepsilon$ and $\bar{\varepsilon}$, have a large influence on the number of rules and the error performance measures. High values of both parameters will result in a small number of fuzzy rules and vice versa. It is also to note that the accept ratio value will determine whether the data points that have strong potential of being clusters centres, whereas the reject ratio value will reject all data points with a low potential of being cluster centres, respectively [208]. The quash factor, on the other hand, is used to find clusters that are far from each other. The details of the subtractive-clustering technique/algorithm can be found in [207]. After a few iterations process, the optimum values of the subtractive-clustering parameters were determined. The values for cluster centres ($r_a$), accept ratio ($\varepsilon$), reject ratio ($\bar{\varepsilon}$) and quash factor ($\eta$) are 0.3, 1.0, 2.0, and 0.5 for $ANFIS_Fx$ respectively; whereas 0.35, 2.0, 0.5 and 0.1 for $ANFIS_Fy$ respectively. The plots of input data space for normalised feed force, $F_x$, and cutting force, $F_y$, with their determined or respective cluster centres are shown in Figure 6.8.

Results from applying the optimum subtractive-clustering parameters to the current datasets have produced 9 and 12 Gaussian MFs for $ANFIS_Fx$ and $ANFIS_Fy$, respectively. These MFs are spaced over the range of input parameters, as shown in Figure 6.9. Hence, each of the generated MFs represents one input cluster centre which can be used to generate a single fuzzy rule.
Figure 6.8: Data and clusters in the two dimensions input space for feed and cutting force datasets
Figure 6.9: Initial Gaussian MFs prior to neural network training
(D) Training procedure

Neural network training and fuzzy inferencing of the ANFIS model were performed in several epochs (iterations) using the predetermined 9 to 12 Gaussian MFs and fuzzy rules in order to identify the final ANFIS model for tool wear prediction. Figure 6.10 exhibits the logical structure of the ANFIS model in the form of a flowchart that explains the procedure for developing the fuzzy logic predictive model. The development of ANFIS modelling was carried out using MATLAB v7.9 with Fuzzy Logic Toolbox (Mathworks, Inc). The subtractive-clustering of training datasets and the ANFIS algorithm were initiated by using the `genfis2` toolbox function in MATLAB. This was followed by the determination or definition of ANFIS and subtractive-clustering parameters such as error goal, training step size, and cluster radius, which were carried out by iterations. Final evaluation of the training and checking outputs with their respective inputs were performed using `evalfis` function in the MATLAB fuzzy logic tool box. The hybrid learning algorithms during the training has resulted in the ANFIS parameters shown in Table 6.2.

Table 6.2: Summaries of output parameters after ANFIS training and fuzzy inferencing

<table>
<thead>
<tr>
<th>Parameter Types</th>
<th>ANFIS_Fx</th>
<th>ANFIS_Fy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of input parameters</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Number of output parameters</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Types of MFs</td>
<td>Gaussian</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Number of MFs/fuzzy rules for machining force</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Output function</td>
<td>Takagi Sugeno First Order Linear Function</td>
<td></td>
</tr>
<tr>
<td>Number of nonlinear parameters, $\alpha_i$</td>
<td>54</td>
<td>72</td>
</tr>
<tr>
<td>Number of linear parameters, $\alpha_i f_i$</td>
<td>36</td>
<td>48</td>
</tr>
<tr>
<td>Number of training data pairs</td>
<td>209</td>
<td>209</td>
</tr>
<tr>
<td>Number of checking data pairs</td>
<td>36</td>
<td>36</td>
</tr>
</tbody>
</table>

Repeated training and checking of the ANFIS models were performed until the minimum training error from the least square estimates has been achieved, Figure 6.11. It can be seen that training of neural networks reaches stabilisation in terms of RMSE at about 200 epochs or iterations. It was determined that the minimum value of RMSE for the $\text{ANFIS}_F_x$ and $\text{ANFIS}_F_y$ after the neural network training was 0.0176 and 0.0209 respectively.
**Procedure in MATLAB for ANFIS modelling**

1. **INPUT**
   - Input the pre-processing data (normalised and randomised data)
     \[ r_i = 0.1 + 0.8 \left( \frac{d_i - d_{\text{pres}}} {d_{\text{max}} - d_{\text{min}}} \right) \]
   - Divide the input into training and checking datasets

2. **Input Space Partitioning**
   - Subtractive Clustering
     - Use: `genfis2`
   - Define sub-clustering parameters
     - (1) Range of cluster centre
     - (2) Range of xBounds
   - Generate fuzzy rules based on number of clusters in `genfis2`

3. **Determine the initial MFs prior to ANFIS training**
4. **Train the data points using `anfis`**
   - Define:
     - (1) Epoch number
     - (2) Error goal
     - (3) Training step size
     - (4) Step size decrease and increase rate

5. **Determine the training and checking errors**
6. **Evaluate the training data checking data using: `evalfis`**
7. **Determine the final MFs after ANFIS training**
8. **Perform statistical analyses to evaluate the ANFIS training output, \( r^2 \), RMSE, cov, plotregression**

**Evaluate**
- Terminate when the results are satisfactory

**Figure 6.10: Flowchart of ANFIS development phases**
The fuzzy rules formulated from the ANFIS models are given in Appendix 6-1. These rules reflect the physical properties of the predictive model along with the membership functions, and were implemented using Takagi Sugeno type FIS in the MATLAB Fuzzy Logic Toolbox environment. As a result of neural network training and fine-tuning of the FIS, the final Gaussian MFs curves for each input have changed from the original shape, as depicted in plots of MFs in Appendix 6-3.
6.3 Results and Discussion

The predicted values of tool wear have been attained once the training and validation procedure of ANFIS model were finalised. ANFIS predicted outputs were compared with the experimental data for different machining parameters employed. The regression outputs from the tool wear-machining forces relationships reported in Chapter 5 were also plotted in the same graph for comparison purposes. It is necessary to recap that the constitutive relationships developed from the previous chapter are as following, for feed, $F_x$, and cutting, $F_y$, forces, respectively:

$$MRA_{F_x}: TW = 10^{-2.547} \times v^{0.409} \times f_r^{-0.564} \times F_x^{1.150}, \quad R^2 = 0.851, \quad \text{Eq. 6.10}$$

$$MRA_{F_y}: TW = 10^{-3.382} \times v^{0.694} \times f_r^{-1.296} \times F_y^{1.667}, \quad R^2 = 0.821, \quad \text{Eq. 6.11}$$

Figure 6.12 depicts a comparison of experimental and the predicted tool wear using feed force, $F_x$, datasets under four different cutting speeds employed with a constant feed rate, $f_r$ of 0.24 mm/rev. It is evident that the tool wear-feed force curve shows a linear relationship when the magnitude of force is in the lower range (under approximately 60 N). Predicted tool wear from $ANFIS_{F_x}$ and $MRA_{F_x}$ models exhibit nearly the same results, in which the difference between them can hardly be distinguished. This is the case when the lowest cutting speed of 110 m/min was employed, Figure 6.12 (a). Nonetheless, when high cutting speeds and machining force data were considered, the predictions from these two modelling methods display their apparent differences. Notably, the ANFIS model is able to closely match the tool wear-feed force relationship when machining forces increase. Likewise, when using cutting force, $F_y$, data, the relationship displays similar trends, Figure 6.13.

Overall, the developed ANFIS models have shown a remarkable match to the experimental data in all of the cases studied, especially when the relationships are nonlinear in the high machining force region. As a matter of fact, with the hybrid learning algorithms of gradient descent, backpropagation network and the application of nonlinear Gaussian functions as the fuzzy logic MFs, a highly accurate prediction of the tool wear has been displayed throughout the entire machining force range. Judging from
the average percentage error between predicted models and the experimental data for these selected cases, it is indicated that ANFIS \(_F_x\) is more accurate in predicting the tool wear when compared to that of ANFIS \(_F_y\). The average percentage error of \(\text{ANFIS}_F_x\) was found to be 8.70\%, whereas, the error for \(\text{ANFIS}_F_y\), was 12.47\% for the machining parameters considered in this section. Conversely, the MRA predicted results display a continuous linear relationship between tool wear and the machining forces throughout all machining force levels. It is apparent that the change in the relationships, particularly in the high machining force range, could not be closely related by MRA techniques. It is imperative to recall here that the continuous linear relationship between tool wear and the machining force is due to the linear interpolative nature of the regression analysis.

![Figure 6.12](image)

Figure 6.12: Comparison of the predicted tool wear from ANFIS and MRA models with the experimental data using feed force, \(F_x\) (for different cutting speeds and a constant feed rate, \(f_r\) of 0.24 mm/rev)
When the new datasets were used to validate the trained ANFIS models, excellent fitting of predicted values against experimental data is also displayed. The curves of tool wear-machining forces for checking datasets of selected parameters are shown in Figure 6.14 (more results from some other parameters are in Appendix 6-4), whereas their statistical performances are discussed in the next section.
Figure 6.14: Comparison of the predicted tool wear from ANFIS and MRA models with the experimental data from the checking datasets.
6.4 Statistical Analyses

Since the results discussed earlier were only for the selected combinations of machining parameters, it is vital to evaluate the accuracy of the developed ANFIS models for the entire machining parameters investigated. These evaluations can be performed using statistical indices to determine the statistical error measures. These indices are namely the root mean square error (RMSE), the coefficient of variation (cov.), the absolute fraction of variance (r²) and the mean absolute percentage error (MAPE). The corresponding equations for these statistical error measures are as follows:

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{m}(y_{\text{pred},i} - y_{\text{exp},i})^2}{m}} \quad \text{Eq. 6.12}
\]

\[
cov. = \frac{\text{RMSE}}{\overline{y_{\text{exp}}}} \quad \text{Eq. 6.13}
\]

\[
r^2 = 1 - \frac{\sum_{i=1}^{m}(y_{\text{pred},i} - y_{\text{exp},i})^2}{\sum_{i=1}^{m}(y_{\text{exp},i})^2} \quad \text{Eq. 6.14}
\]

\[
MAPE = \frac{\sum_{i=1}^{m}(\frac{y_{\text{pred},i} - y_{\text{exp},i}}{y_{\text{pred},i}}) \times 100}{m} \quad \text{Eq. 6.15}
\]

where, \(y_{\text{pred},i}\) and \(y_{\text{exp},i}\) are the predicted value and experimental data of the tool wear respectively, \(\overline{y_{\text{exp}}}\) is the average experimental data of tool wear and \(m\) is the number of the sample. Table 6.3 exhibits the results of statistical performance for each of the developed predictive models. The accuracy and improvement of ANFIS predictive capabilities are apparent when compared to those of the MRA. For instance, a significant increase of the \(r^2\) values from the MRA models to the ANFIS models can be observed particularly for the training data. A value of 1.0 indicates perfect prediction.
Evidently, the $r^2$ values for each developed ANFIS model show a closer value to 1.0 compared to the values obtained from the MRA models. The values of RMSE, $cov.$ and MAPE, in contrast, have shown substantial reduction when the predicted results from ANFIS models are compared to those from the experiment and MRA models.

Additionally, the statistical errors for the predicted values of the validation datasets were found to be remarkably close to those from the training datasets. Hence, this indicates that the developed ANFIS models can be generalised for all of the experimental data gathered. As highlighted in the previous chapter, the inherent variations, fluctuations or noises in the measured cutting force, $F_y$, result in a less accurate predictive model for tool wear. This is anticipated, as the results of MRA techniques discussed earlier in Chapter 5 exhibited similar trend. The statistical indices in Table 6.3 also validate this finding.

<table>
<thead>
<tr>
<th>Statistical Indices</th>
<th>MRA_Fx</th>
<th>ANFIS_Fx</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r^2$</td>
<td>0.9789</td>
<td>0.9920</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.0294</td>
<td>0.0181</td>
</tr>
<tr>
<td>$cov.$ (%)</td>
<td>15.52</td>
<td>9.559</td>
</tr>
<tr>
<td>MAPE (%)</td>
<td>12.64</td>
<td>8.20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Statistical Indices</th>
<th>MRA_Fy</th>
<th>ANFIS_Fy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r^2$</td>
<td>0.9744</td>
<td>0.9889</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.033</td>
<td>0.0213</td>
</tr>
<tr>
<td>$cov.$ (%)</td>
<td>17.50</td>
<td>11.29</td>
</tr>
<tr>
<td>MAPE (%)</td>
<td>15.14</td>
<td>8.66</td>
</tr>
</tbody>
</table>

Similar to Chapter 5, the scatter diagrams, Figure 6.15 (c-d), were plotted to demonstrate the accuracy of the predicted tool wear from ANFIS models with respect to the experimental data. For comparison purposes, the scatter diagrams of the MRA predicted...
values are shown as well, Figure 6.15 (a-b). It is clear that almost all ANFIS predicted values clustered within the ±15% error and close to the 45° line (for perfect prediction). This indicates the substantial improvements in the tool wear predictive capability for both $ANFIS_F_x$ and $ANFIS_F_y$ models. The predicted values from the validation datasets also demonstrate the closeness to the perfect prediction line (the 45° line), Figure 6.15 (c) for the $ANFIS_F_x$ model. In comparison, the predicted values from $ANFIS_F_y$ training datasets as well as the validation datasets exhibit a slight variation from the experimental data, Figure 6.15 (d). This evidence is truly conclusive that feed force alone can effectively be used as an input in determining the extent of tool wear during machining of GFRP composites. This is judged from the results of statistical indices and scatter diagrams presented here, as well findings from Chapter 5.

![Scatter diagrams of predicted values against experimental data for (a) MRA$ _F_x$ (b) MRA$ _F_y$, (c) ANFIS$ _F_x$ and (d) ANFIS$ _F_y$](image)

Figure 6.15: Scatter diagrams of predicted values against experimental data for (a) $MRA_F_x$, (b) $MRA_F_y$, (c) $ANFIS_F_x$ and (d) $ANFIS_F_y$
Since a wide-range of machining parameters has been employed, it is possible to plot 3D surface diagrams of predicted values obtained from each modelling technique and superimposed with the experimental data. 3D surface diagrams are particularly useful as a visual base predictive tool for monitoring the extent of tool wear for the machining of GFRP composites. These plots also provide a clearer representation of how well the predicted values fit the experimental data. From these plots, it is evident that the MRA predicted values show the linear trend within all of the force magnitudes, as mentioned earlier. Notably, the accuracies of the ANFIS models are well pronounced throughout all machining force levels as shown in Figures 6.16 – 6.17. As indicated earlier, the apparent difference between MRA and the ANFIS can be easily noticed in the high machining forces and parameters region.

6.5 Concluding Remarks

The ANFIS models presented in this chapter show the potential of modelling the complex and nonlinear relationships between tool wear and machining forces during end milling of GFRP composites. As elaborated in Chapter 5, the extent of tool wear can be satisfactorily monitored without interrupting the cutting process by using the developed relationships between tool wear and machining forces from MRA. However, the inherent anisotropic and non-homogeneous natures of GFRP composites are likely to cause variations in machining forces measurement. Due to these facts, it is often difficult to accurately establish constitutive tool wear-machining forces relationships by the method of statistical or regression analysis.

The development of ANFIS models in this chapter has demonstrated a substantial improvement in the accuracy of predicting the tool wear. Results from the developed ANFIS models exhibit highly accurate predictive capabilities especially when the constitutive relationships are nonlinear. The ANFIS superiority is attributed to the hybrid learning algorithms of backpropagation and gradient descent network, sub-clustering of datasets as well as the application of the nonlinear Gaussian functions for the fuzzy inferencing. Using the developed models, MRA equations or ANFIS models, a timely decision on tool reconditioning can be achieved. This prevents any adverse
effect of the worn tool on the machined GFRP composites apart from minimises loss in machining productivity due to machine downtime.

Figure 6.16: 3D surface diagrams of (i) MRA and (ii) ANFIS predicted data superimposed with the experimental data for feed force, $F_x$, at (a) $f_r$ of 0.16 mm/rev and (b) at $v$ of 150 m/min
Figure 6.17: 3D surface diagrams of (i) MRA and (ii) ANFIS predicted data superimposed with the experimental data for cutting force, $F_y$, at (a) $f_r$ of 0.24 mm/rev and (b) at $v$ of 150 m/min
Chapter 7 Chip Formation Studies

7.1 Introduction

The study on chip formation during machining operation has served a pivotal role on the fundamental insights into the mechanics of material removal. This study has proven to be effective for materials’ machinability evaluations and has received considerable attentions among researchers worldwide. Indeed, two well-known theories with regard to chip formation for metal cutting, namely ‘the adiabatic shear theory’ and ‘the crack theory’ [209], have been regularly used to analyse the primary shear or deformation zone. However, it is imperative to highlight that the nature of the chip formed is not only associated to the changes in the shear zone. Material properties, which include ductility, hardness, thermal conductivity, and microstructures, also highly govern the chip forming mechanisms [19]. In addition, undesirable phenomena such as instabilities during cutting process and deterioration of tool sharpness can alter the chip formation process quite significantly [209].

Chip formation study for FRP composites is often difficult due to their in-homogeneity and pronounced anisotropy. Adding to that, these materials exhibit very little plastic deformation or if any at all, compared to that of homogenous and ductile materials [3]. Obviously, the chip formation theories explained for metallic materials may not be appropriate to describe the mechanics of chip creation during machining of the FRP composites. The various types of fibre reinforcements and their architectures also limit any conclusive or generalise theories associated to the chip formations for these composite materials.
Nonetheless, these do not imply that their chip formation studies are less attractive compared to the metals. As a matter of fact, the earliest research efforts on the examination of chip formation during machining of FRP composites were reported by Koplev et al., Arola et al., and Bhatnagar et al., back in the mid-1990s [9, 102, 193]. Both Koplev et al. and Arola et al. asserted that chip formations consist of a series of fractures which create highly diverse fragments of fibres and matrix materials [102, 193]. As expected, machining parameters essentially affect the types of chip being formed; e.g.: sizes and shapes. Adding to that, fibre direction or orientation, also strongly influenced the nature of chip; as outlined in Chapter 2. In all of those reported studies, the ‘quick-stop’ method, which has been developed for the metal cutting, was employed for the ‘in-situ’ microstructure analysis of the formed chip. This is despite the dissimilarity in the chip formation mechanisms between metal and FRP composites.

It is well known that a quick-stop device (QSD) is an established tool which is commonly used for fundamental study on chip formation during metal cutting. This device arrests a machining operation by rapidly disengaging the cutting tool from the workpiece material or vice-versa. Therefore, this allows the extraction of resulting chip root, as its strains, for subsequent microscopic analyses. Nonetheless, several researchers have claimed that there exists a tool-chip separation delay during the tool or workpiece retraction while the quick-stop device is in operation [210, 211]. This delay, which is dependent upon the design of the employed device, may considerably alter the state of chip deformation. Hence, the results may not accurately represent the dynamic changes of the machining process.

As a result, high-speed filming or photography provides an option or alternative to effectively study the chip formation during a machining or cutting operation. Indeed, this was demonstrated by Komanduri and Brown, in which they have successfully presented images of segmented chips during orthogonal cutting of the cold-rolled steel [212]. Chip segmentation processes were recorded using a high-speed camera at 3300 frames per second (fps) for cutting speeds up to 55 m/min. The results allowed them to conclude that the chip segmentation process was mainly attributed to the instabilities of the cutting process. The authors then verified the video photographic observations of
chip formation with comprehensive microscopic studies of the chip root obtained from the quick-stop device.

Until recently, several researchers have also reported the effectiveness of using high-speed filming/camera to observe the chip forming process for various metallic materials [210, 211, 213]. However, it is worthwhile to note that the acquisition of quality pictures in high-speed photography requires compromise between recording speeds, image resolutions, adequate lighting, high contrast, depth of fields, and exposure time [212, 213].

On the other hand, very few studies in the past, have attempted a comprehensive characterisation of chip formations and morphologies while end milling of GFRP composites. This chapter reports on such study. The setup of high-speed photography, which consists of a high-speed video camera in conjunction with the high-intensity lighting, has been employed for this purpose. This high-speed photography is used in order to observe the dynamic or phenomenological changes on the nature of chip being formed during cutting operation.

There has been limited information with regard to a QSD for interrupted machining operation such as milling. One such study was reported by Kopac et al. [214] for metal cutting. However, the detailed discussion about the construction of QSD cannot be found, which could question the results presented. Due to the unavailability of any QSD for milling operation, the current study has developed an apparatus/setup to perform the quick-stop procedure. This setup allows the end mill cutter to be frozen instantly, which preserves the uncut chip on the workpiece material. Subsequently, microscopic analyses were performed on the chip root to characterise the nature of chip segmentations and morphologies.
7.2 Experimental Setup

The chip formation studies in this chapter have been accomplished using experimental setup and machining parameters discussed as follows:

7.2.1 End milling experiments and cutting parameters

The use of CNC milling centre (as shown in Chapter 3) for high-speed photography of chip formation for the GFRP composites was initially found to be problematic. This is mainly due to the space limitations on the CNC machine to position the camera at the suitable angle. Thus, it was decided to use the conventional vertical milling machine, MAXIMART, which offers better space and flexibility on the video camera placement. This machine has a spindle power of 2.2 kW and the maximum spindle speed of 2,800 RPM. The uncoated tungsten carbide end mill tool was used for the study herein. Machining parameters for the chip formation studies are given in Table 7.1. Such selection of parameters can be justified by three reasons:

- To alleviate the effect of tool wear during the cutting process;
- To facilitate the preservation of unbroken chip during quick-stop procedure;
- To ensure production of robust chip for subsequent microscopic analyses.

It has been found, initially, that conducting the tests at the previously used machining parameters (as in earlier chapters) have resulted in improper chip formation. This is due to the fact that, at the harsher machining parameter (e.g. spindle speed > 1,000 RPM), the chip experiences a significant increase of strain, which intensifies fracture failures. As shown in the SEM images depicted earlier in Chapter 4, Figure 4.17, the chips were mainly in the form of dusts of micro-sized particles due to the high strain applied to the workpiece material under the employed machining parameters. Unfortunately, this type of chip reveals very little information about the chip forming processes. Hence, the machining parameters were lowered so that desirable chips can be produced to facilitate further microscopic examinations. These parameters are given in Table 7.1.
Table 7.1: Machining parameters for chip formation studies

<table>
<thead>
<tr>
<th>Workpiece material</th>
<th>Uni-directional GFRP composites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool</td>
<td>Single flute K20 end mill cutter</td>
</tr>
<tr>
<td></td>
<td>12 mm diameter</td>
</tr>
<tr>
<td>Machining parameters:</td>
<td></td>
</tr>
<tr>
<td>Spindle speed, (s)</td>
<td>100, 300, 500 RPM</td>
</tr>
<tr>
<td>Linear effective speed, (v)</td>
<td>3.77, 11.30, 18.84 m/min</td>
</tr>
<tr>
<td>Feed rate, (f_r)</td>
<td>0.32 mm/rev</td>
</tr>
<tr>
<td>Axial depth of cut, (d_a)</td>
<td>3 mm</td>
</tr>
<tr>
<td>Radial depth of cut</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Fibre orientation, (A)</td>
<td>0°, 45°, 90°</td>
</tr>
</tbody>
</table>

7.2.2 High-speed photography settings

Two essential elements for a high quality image acquisition during the high-speed photography often compose of (1) high-speed camera, and (2) lighting. Machining parameters can be set at high levels during the setup in order to take the advantage of the high-speed camera capabilities. However, larger sampling size, short exposure time, and high-intensity of light on the viewing area will then be essential. Besides that, to study the details of the cutting process, the image of the subject of interest need to be magnified quite considerably. This, in turn, requires an increase in the depth-of-field which will compromise on the aperture settings, lens focusing, and consequently the intensity of the light.

A high-speed video camera, the Phantom V210, having maximum recording speed of 300,000 fps and a full resolution (1280 x 800) recording capability of 2000 fps, has been used for filming of the chip formation. A well-focused footage of the cutting zone in the present investigation has been achieved using two-COOLH Dedocool tungsten head lights. These lamps provide a high-intensity concentrated light on the interested viewing area. Figure 7.1 depicts the general setup for this experiment.
It is well known that end milling is a 3-dimensional cutting process which involves a complex oblique cutting operation on the workpiece material. Due to helical geometries of the end milling cutter, the view of the cutting zone may be obstructed when machining is performed with full immersion of the cutting tool into the workpiece material. Therefore, to facilitate the viewing window of chip formation during cutting operation, side end milling process has been chosen, Figure 7.2 (a). It is to note that three out of four cutting flutes were purposely ground to ensure that the interested cutting zone was not blocked by the progressing cutting flute. Figure 7.2 (b) depicts the modified end mill cutter. Radial depth of cut, $d_r$, of 0.5 mm has been selected for this side end milling process. For the set of machining parameters employed, the chip formation process can be best captured at the 640 x 480 pixels resolution with recording speed of 1,000 to 3,000 fps.
Figure 7.2: (a) Side end milling of GFRP for filming of chip formation process and (b) modified end mill cutter

7.2.3 Quick-stop arrangements

The working principle of the common QSD is through arrangement of shear pin, which is broken via impact, to consequently allow rapid separation of the tool from the cutting zone. Explosive charges are normally used to break the shear pin, accelerating the tool away from the cutting coupon. This design can be easily implemented under orthogonal cutting or continuous turning processes which uses a single point tool. Unfortunately, the use of this device would be impractical, if not impossible for milling process due to intermittent cutting nature of milling operation. The ideal instant separation of the cutting tool from workpiece material may not be practically achievable in milling as it does in turning operation.

In fact, the rapid movement and interruption of either the workpiece material or the cutting tool, while preserving the chip on the GFRP workpiece could be very challenging. This is because the uncut chip may possibly or easily be broken-off due to the properties of these composite materials. Hence, this section elaborates on the effort to setup an arrangement; which enable the preservation of an uncut chip on the GFRP
composites while cutting is in operation. The method employed is different from that of the common quick-stop device used in orthogonal cutting or turning operation. In general, it involves a simultaneous halting of tool rotation and table feed via configuration of a tripped switch, braking system, and a pneumatic ram, Figure 7.3.

Basically, the OSISWITCH tripped switch, which was fitted on the milling machine as shown in Figure 7.3 (b), serves as the electrical switch to break/cut off the power on the machine during operation. This tripped switch was simultaneously triggered as the force is applied on the brake lever to stop the tool from continuously rotates. At the same time, the switch also sent a signal to the machine controller box to activate the fitted pneumatic ram, Figure 7.3 (c). The movement of the ram then pushes on the feed table lever to disengage the feed table gear, whereas, the disengagement of feed table gear ensures that the motion of table feed is instantaneously halted. Each of these configurations is shown in Figure 7.3 (b-c).

Observations have been made under the high-speed video camera in determining the stopping time of the tool and the table feed motion while this quick device is in operation. The results were within one tenth of a second, which is fairly adequate considering the mild machining parameters employed. Subsequently, the tool was carefully removed from the cutting cushion so as to preserve the unbroken chips. Samples of these chips under different test machining parameters were then prepared for the microscopic analyses.
Figure 7.3: (a) Quick-stop arrangement on the milling machine, (b) the fitted trip switch and (c) pneumatic ram

7.3 Results and Discussion

7.3.1 Results from high-speed camera

(A) Effects of cutting speed on chip size

Figure 7.4 presents photographic frames of chip formation recorded using the setup discussed earlier and for the tool rotational speed of 100 RPM with feed rate of 0.32 mm/rev. In general, information disclosed by the high-speed photographic footages show that a fairly defined chip can be formed as the tool cutting edge sheared along the fibre orientation, Figure 7.4 (a-b). A layer of delaminated chip was observed to be peeled...
up along the tool rake face prior to the bending and buckling-induced fracture as the tool exits the workpiece material, shown in the oval shape of Figure 7.4 (c). Apparently, the chip has shown a little tendency to curl up along the rake face due to the helical nature of the tool. However, the lack of sufficient ductility on the FRP composites restricted further deformation process of the chip, as expected. As the tool disengaged from the workpiece material, appearance of the chip-ends reveals some evidence of fibre pull-out and delamination, as shown by the arrow in Figure 7.4 (e). Judging from these photographic images, the features of the formed chip confirm to be the ‘Mode/Type I’ chip formation during orthogonal cutting of FRP composites proposed by Wang et al. [101, 102]. ‘Mode I’ chip formation is defined as the fracture of a chip which propagates along the fibre-matrix interface as the chip undergoes shear. At one point during cutting, the chip is released due to buckling and bending failures [102]. Although, these static images may not truly represent the dynamic changes of the chip; however, they are more or less display the information. Evidence from these video footages also exhibited the absence of plastic deformation during machining of FRP composites in all of the cases considered.

SEM images of the machined sample shown in Figure 7.5 substantiate the buckling and bending induced fracture of the fibre reinforcement on the machined surface. The fractures seem to occur ahead of the cutting edge and perpendicular to fibre direction. Appearance on the machined surface and individual fibres distinctively shows the evidence of bending failures and delamination due to the action of tool cutting edge, shown by the ovals in Figure 7.5 (a). In fact, the segment of fragmented chip collected clearly reveals that the fibres have been being pull-out from the GFRP workpiece, as depicted by the arrow in Figure 7.5 (b). This leaves behind irregular or rougher machined surface as pointed by the ovals in Figure 7.5 (a). To some extent, this concurs with the results obtained under the employed machining parameters discussed earlier in Chapter 4. The irregular and rough machined surface attributed to the variations of $R_a$ values shown in Figures 4.7 – 4.8 of Chapter 4. Eventhough the machining parameters are relatively lower than that of Chapter 4 (especially for the spindle or cutting speed), it has been found earlier in Chapter 4 that the effect of this parameter on surface quality or damage is negligible. Hence, it can be concluded that the damage or surface finish quality found in this part of study is more or less equivalent to that of Chapter 4.
Figure 7.4: Frames from video footage during chip formation of side end milling GFRP composites at $s$ of 100 RPM, $f_r$ of 0.32 mm/rev and $A$ of 0°
Figure 7.5: SEM images of machined surface and segmentation of chip collected at fibre orientation, $A$ of 0° and $s$ of 100 RPM, $f_r$ of 0.32 mm/rev

The increased cutting speed of 300 and 500 RPM have caused the chip to be fractured or broken-off into smaller segments even before the tool disengaged from the workpiece material, Figure 7.6. This process is augmented through the high stress/load exerted by the rotating cutting tool on the chip surface at the elevated speed. Insufficient adhesive strength between epoxy matrix and the fibre reinforcements could likely to cause the splitting of the chip into smaller segments. It also appears from the microstructures of the collected chip that the fibre reinforcements were partially debonded from the polymer matrix, as depicted in the white coloured box, Figure 7.7. Apparently, debris of epoxy matrix is seen to accumulate on the top surface of the fractured fibre reinforcement as a result of epoxy matrix brittle fracture, which left the fibres to loose.

Figure 7.6: Frames from video footage during chip formation of side end milling GFRP composites at $s$ of 300 RPM, $f_r$ of 0.32 mm/rev
(B) Effects of fibre orientation

The machining tests were extended to cutting at the 45° and 90° fibre orientation (with respect to tool feed). The results show completely different phenomena from those discussed previously. Even under the lightest parameter tested, the photographic frames of the cutting sequences reveal no distinct chip formation. Instead, as soon as the tool came into contact with the workpiece material, parts of the chip were observed to be shattered into powdery particles of fibres and epoxy matrix. As the cutting progressed, the rate and the number at which the segmental chips segregated into smaller size accelerate and also stochastic in nature. Unfortunately, from the photographic frames of the captured video (shown in Appendix 7-1); it was difficult to clearly denote any chip formation process due to the nature and reduction of the chip size and shape. It is worthwhile to note that the mechanisms observed from the images appear to be consistent with those documented in past research during orthogonal cutting of the FRP composites [101, 102, 109]. The authors claimed that these phenomena were attributed to the out-of-plane fracture of the fibre reinforcement. However, evidence from the video footages suggests that fracturing of the chip is predominantly due to crushing-compression of the progressing cutting tool onto the workpiece material.
Despite the random size of chips while machining at the 90° fibre orientation, the chips were carefully collected using a double sided adhesive tape for subsequent microscopic studies. Clearly, one distinct feature of the chip is that the fibres are still being held by the epoxy matrix. As observed under the SEM, Figure 7.8 (a), the distribution of epoxy matrix is still intact within the fibre bundles. This could be likely due to the reduced length of the fractured chip that got separated from the tool rake face. As a result, the chip did not tend to curl or slide up the tool rake face during cutting. This curl or slide up effect may be one of the main causes for the brittle fracture of the epoxy resin as the tool exerts stress on the chip during cutting.

The appearance at the end vicinity of individual fibres reveals the bending and brittle fracture of the glass fibres which could be subjected to shearing, tensile or bending stresses. It is evident that the fractured surface of the glass fibre appears to be smooth due to its amorphous and brittle nature, Figure 7.8 (b). Morphologies of the fractured fibres also show that the bending and brittle failures occurred at random positions along the fibre directions. These failures create irregular machined surface with the fibre ends ‘sticking-out’ at varying lengths, Figure 7.8 (c) [3]. The direct contact between these fibres and tool cutting edges is the major cause of abrasive wear on the cutting tool while machining these FRP composites, as described in the earlier chapters. Obviously, friction or rubbing of the fibres onto the tool flank face abraded the cobalt binder between the tool WC grains and fractured them into smaller sizes, as discussed in Chapter 4.

7.3.2 Results from quick-stop method

Meanwhile, the unbroken or preserved chip on the machined surface obtained from the quick-stop method was carefully cut out from the workpiece. The samples were prepared and examined under SEM to acquire information regarding morphologies of the chip root. The typical microscopic photographs of the uncut chip are shown in Figure 7.9. As apparent, the preserved chip exhibited an oblique shearing of the material due to the cutting tool geometry. Parts of the deformed chip can be seen to be broken off from the bigger chunk of chip. Indeed, a closer examination on the back and remaining chip surface has shown crack initiation between the bonding of fibre reinforcement and epoxy matrix, depicted by the arrow and the box in Figure 7.9 (a-b). This crack promotes
Figure 7.8: (a) SEM images of morphologies of the collected chip while cutting at 90° to fibre orientation, (b) close-up of fractured fibres and (c) sticking-out of fibre from machined surface
the splitting of chip into smaller segments as depicted in Figure 7.9 (c). Similar to that observed by Puw and Hocheng [215], the compressive force exerted by the cutting tool compels the chip to fail due to bending and buckling, Figure 7.9 (d). The failures were observed to be along the fibre direction and accompanied by considerable brittle fracture of the weaker epoxy matrix due to the high cutting speed employed. This matches the results obtained from the high-speed photography of chip formation discussed earlier.

7.4 Concluding Remarks

The following concluding remarks can be made based on the results observed herein:

– Insufficient ductility and non-homogeneous properties of GFRP composites have produced discontinuous and fracturing chip during machining operation.

– Morphologies of the collected chip and machined surface revealed the bending, buckling, fracture, delamination, and crushing-compression of the fibre reinforcement and matrix material. These various modes of material failures or fractures seem to occur randomly along the machined surface.

– Under the lightest cutting speed tested, a layer of delaminated chip was seen to be peeled along the rake face of the cutting tool. However, an increased cutting speed has resulted into smaller chip segmentations. This was mainly due to the increased stress on chip surface and weak adhesive bonding between the fibres and the epoxy matrix.

– When machining at 45° and 90° fibre orientation, the chips were observed to be shattered into powdery particles of fibres and epoxy matrix due to the out-of-plane fracture and crushing compression of the progressing cutting tool on the workpiece material. These failures make it difficult to denote any chip forming mechanisms.

– Although the designed QSD can be fairly used to preserve unbroken chip during machining, its robustness can be further improved for future studies that involve high machining parameters.
Figure 7.9: SEM images of chip root obtained from quick-stop method SEM images of chip root obtained from quick stop method for (a-b) $S$ of 300 RPM, $f_s$ of 0.32 mm/rev and $A$ of 0°; (c) $S$ of 500 RPM, $f_s$ of 0.32 mm/rev and $A$ of 0° and (d) $S$ of 500 RPM, $f_s$ of 0.32 mm/rev and $A$ of 90°.
Chapter 8 Conclusions

8.1 Conclusions

The primary objective of this research was to systematically address the machinability issues of GFRP composites. It is well known that the inherent properties and distinct anisotropy make the GFRP composites machining difficult. The complexity of cutting mechanisms associated with end milling also adds their existing poor machinability. Hence, this thesis has presented an elaborate characterisation of end milling the GFRP composites focusing on key machinability indices, namely the tool wear/life, surface finish, machining forces, and the chip forming mechanisms.

Although each of the earlier chapters has provided distinctive concluding remarks, this chapter recapitulates the main contributions and accomplishments of the entire research programme. These can be summarised as follows:

a) Parametric study
The effects of machining parameters on the key machinability outputs or indices have been effectively/successfully investigated through Taguchi design of experiment. A set of desirable or practical end milling parameters (guided by the end applications) has been successfully determined and evaluated. In general, it appears that feed rate is the governing parameter which influences the surface roughness, the machining forces as well as the tool life. As a matter of interest, results from Taguchi analyses and ANOVA have converged to the same conclusion with regard to the parametric influence of the feed rate. The depth of cut is deemed to have the least effect on the surface roughness and tool wear/life, but is equally dominant (along with the feed rate) on the machining
forces. Meanwhile, increasing spindle speed is expected to accelerate tool wear and reduce the tool life. However, results from this parametric study have shown that the increase in tool wear is minimal due to changes in the spindle speed.

As expected, surface finish of the machined samples deteriorates with the increase of feed rate, whereas it marginally improves with the increase in spindle speed. The results have highlighted that an increased feed rate accounted for various mechanisms of chip formation, which promotes inter-laminar failures and fractures of the glass fibres and epoxy matrix to deteriorate the surface finish. However, the inherently large variations in the surface roughness readings may give dubious results of the machined surface quality. Indeed, investigations on the morphologies of the machined surface under the SEM have conspicuously revealed the various modes of machining induced damage. This comprises fibre fracture, pull-out and/or protrusions, delamination damage, and fracture of epoxy matrix.

b) Failure of cutting tool
Flank wear has been observed to be the dominant tool failure mode throughout the employed machining parameters. Mechanical abrasion, due to the contact and rubbing actions of the fibres on the tool material, has been confirmed to be the primary wear formation. Abrasion mechanisms, which accounts for the removal of cobalt binder and fracture of the cutting tool’s WC grains, have been successfully observed under the SEM. Due to the intermittent cutting action of end milling operation, some micro-chippings of the cutting tool edges were also found to exist.

c) Effect of fibre orientation
It is apparent that the growth of tool wear prior to reaching the predefined tool life criterion is substantially reduced when the machining test was performed across the fibre orientation (90° fibre orientation). This is compared to the case when the tool or machine table was fed along the fibre direction (0° fibre orientation). The difference in the growth rate of tool wear is most likely due to the tool-fibre contact mechanism during machining. In spite of this, the presence of burrs or uncut fibres and some severe delamination on the top side of the machined surface have offset this superior tool life performance. It has been highlighted that the more severe cutting parameters (e.g.}
increased cutting or spindle speed and feed rate) do not seem to improve the quality and quantity of the uncut fibres either. Hence, it is concluded that better machinability (with respect to surface quality) can be achieved when machining is carried out along the fibre orientation, even though the tool wear rate is relatively high.

d) Taylor’s tool life model
Initial parametric study (through Taguchi factorial design of experiment) has shown some dubious results as far as the effect of spindle or cutting speed on tool life is concerned. However, this has been reconciled by incorporating a wider range of machining parameters in the full factorial experimental studies. Based on the derived Taylor’s tool life models, it is confirmed that the cutting or spindle speed has the strongest effect on the time for the cutting tool to reach at its predefined tool life.

The two fibre orientations have shown only small influence on the tool life. This is despite the fact that machining across the fibre orientation eases the growth of the tool wear and results in a longer time to reach the tool useful life. It has been asserted that the effect of changing fibre orientation for the GFRP composites is not high enough to offset the results of severe or harsher machining parameters on the tool wear/life. This can be judged from the values of Taylor’s equation exponents as well as the curves of tool wear growth. The tool life equation developed empirically as a function of the cutting speed, \( v \) and feed rate, \( f_r \) is:

\[
TL = 10^{7.279} \times v^{3.161} \times f_r^{-0.422} \quad R^2 = 0.969
\]

whereas, when taking into account the effect of fibre orientation, \( A \), the extended Taylor equation is given by:

\[
TL = 10^{0.351} \times v^{0.722} \times f_r^{-0.251} \times A^{0.445} \quad R^2 = 0.946
\]

It is imperative to highlight that the Taylor’s predicted tool life yields excellent agreement to the experimental data within the tested range. Superior predictive capabilities are also evident on the randomly chosen settings, which are outside of/or
different from that of the planned experimental range. On the basis of cutting time performance, the uncoated tungsten carbide tool exhibits a reasonable range of useful life prior to reaching the predefined tool wear criterion.

e) Machining forces and tool wear-machining force relationships

It has been found from the Taguchi parametric analysis that the increase in cutting speed does not have strong effects on the magnitudes of machining forces as compared to those of the feed rate and depth of cut, particularly at the early stage of machining process. Nonetheless, during the continuous tool wear and machining force monitoring experimental tests, the effects of changing cutting speed were found to be more pronounced as the cutting operation progressed. This is primarily attributed to the deterioration of tool sharpness. The experimental results have also clearly demonstrated that feed rate has a more predominant effect on the magnitude of machining force as compared to the cutting speed. A significant increase in the machining forces has been observed with a higher feed rate and longer machining time, owing to the chip formation mechanisms and reduction of tool sharpness.

Similarities in the development of machining forces and tool wear growth have suggested that the relationships between them can be correlated. As a result, machinability data obtained from the full factorial experiments have been presented in the form of tool wear-machining forces relationships. General power law equations have been developed using multiple regression analysis in describing these relationships. Results have shown that these equations can be used to predict the trend of tool wear with an acceptable or adequate accuracy. The empirical models developed from the wide spectrum of machining parameters, considering feed force, $F_x$ and cutting force, $F_y$ separately, can be expressed as follows:

For feed force-tool wear: $TW = 10^{-2.547} \cdot v^{0.409} \cdot f_r^{-0.564} \cdot F_x^{1.150}$, \hspace{1cm} $R^2 = 0.851$

For cutting force-tool wear: $TW = 10^{-3.382} \cdot v^{0.694} \cdot f_r^{-1.296} \cdot F_y^{-1.667}$, \hspace{1cm} $R^2 = 0.821$

It has then been successfully demonstrated that the developed ‘Adaptive Network-Based Fuzzy Inference System (ANFIS)’ model yields a substantial improvement in the
capability of predicting tool wear throughout the entire experimental range tested. Notably, this fuzzy logic modelling, coupled with neural network training has been able to closely fit the tool wear-machining force trends in the high machining parameter and force regions where the relationship is nonlinear. This can be attributed to the hybrid algorithms back propagation and gradient descent from neural network training apart from the application of nonlinear Gaussian membership for fuzzy inferencing. The technique of subtractive-clustering machining dataset also helps in identifying the optimal number of Gaussian membership functions for the fuzzy inferencing or the construction of fuzzy rules. Comparative statistical evaluations of the predicted values from the training data with the experimental results suggest the superiority of the developed ANFIS models. The ANFIS models have also been successfully validated using the testing data which are different from that of the training data. In spite of the method’s implicit expression, the results are highly appealing for the indirect monitoring of tool wear progression without interrupting the GFRP composites cutting process. Furthermore, judging from the results of surface plots for the tool wear prediction, it is apparent that the nonlinearity relationships of the ANFIS tool wear-machining force lead to a direction of further research into determining or explaining their physical relationships.

g) Chip formation mechanisms
The chip forming mechanisms involving material fractures have been observed under the employed cutting parameters. Information disclosed by the high-speed photography has shown that a peeled layer of delaminated chip was formed as the tool cutting edge fractures along the fibre orientation under a relatively mild cutting speed. This chip can be seen to slide up along the tool rake face in a cantilever beam fashion prior to bending-induced fracture as the tool exits the workpiece material. Evidently, this result confirms the Mode I chip formation during orthogonal cutting of FRP composites reported in the past studies. An increased cutting speed causes the chip smaller, which can be easily be separated or broken-off even before the tool gets disengaged from the workpiece material. This is likely due to insufficient bonding between the fibres and the epoxy matrix to withstand high stress exerted by the tool rake face. As a result, this promotes brittle fracture at the fibre-matrix interface of the formed chip and separates the segmented chip into smaller micro-chips. Microscopic photos of the collected chips
have also shown the evidence of loose fibres because of brittle failure or fracture of the epoxy matrix.

As observed on the video footage, the chips were fractured into smaller fragments as the tool cut at different fibre orientations, e.g. 45° and 90°. In fact, no distinct chip shapes or forms can be noticed even for the lightest machining parameters tested (shown in Appendix 7-1). This concurs with the existing knowledge on orthogonal cutting of FRP composites. Out-of-plane fracture and compression-dominated failures can be attributed to this phenomenon. Closer examinations on the machined surface reveal the evidence of fibre pull-outs, delamination, fibre protrusion, and brittle fracture of epoxy matrix. All of these account for the irregular or rougher surface on the machined GFRP composites and contribute toward the variations of measured surface roughness or $R_a$ values. The irregular machined surface also depicts the ‘sticking-out’ of fibre ends at varying lengths. The direct rubbing of these fibres onto the tool cutting edge was the major cause of abrasive wear on the end mill tool.

### 8.2 List of Publications

**Refereed International Journals and Proceedings**


International Conference Presentations


8.3 Recommendations for Future Work

Comprehensive investigations and understandings on the end milling of GFRP composites have been demonstrated in this thesis. Nonetheless, the studies were undertaken within certain boundaries which future work may be based upon. The following recommendations are outlined:

- It is known that the effects of volume fraction on delamination damage and machining quality during drilling of FRP composites have been discussed by other researchers. However, it is vital to emphasise that there is no clear relationship between volume fraction and the key machinability outputs (e.g. force, tool wear, surface quality and chip formation) during milling operation. Since FRP composites are often fabricated with various fibre contents, different responses may be obtained. This variable could be essential in other future research.

- The results discussed in this thesis were limited to the selected fibre reinforcements (e.g. uni-directional E-glass fibres) and their orientations. Future work should consider extending the machinability assessments to other fibre orientations and fibre architectures (e.g. multi-directional composites). These variables, namely; volume fraction and fibre architectures, could be incorporated in the Taylor’s tool life equations and the tool wear-machining force predictive models. This will eventually complete the end milling GFRP composites predictive models.

- A wide range of uncoated carbide tools should be tested, so that the extent at which the findings of the present work are applicable to other carbide tools can be determined. Tools with different geometries (e.g. single/double helix, rake angles, corner or edge radius) may also be evaluated for better or improved machining qualities.
Conclusions

- The cutting temperature generated by a machining process is generally high enough to affect some of the materials properties significantly. This is especially true for the FRP composites. Its effect should be characterised and incorporated in future research of end milling the composite materials.

- Future research could pursue on using other machining sensors such as accelerometers in monitoring the condition of the cutting tool. Vibration based signals measured from this sensor can be an ideal or potential input to indicate the tool condition while machining the FRP composites.
Appendix 3-1: Calibration of the Kistler® 9265B dynamometer

Kistler® 9265B dynamometer with direction of force components and calibration on the Instron 1185 machine
Appendix 3-2: Calibration curves for force measurement in the $x$, $y$ and $z$ directions respectively

![Graph 1](image1.png)

![Graph 2](image2.png)
Appendix 3-3: SGS 41665 end milling tool basic specifications

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Long and Extra Long Series 1 highlighted above.
Appendix 4-1: Supplementary data for the measured $F_y$ and $F_z$ from the L$_9$ Taguchi experiments

(i)  Cutting force, $F_y$

(ii) Thrust force, $F_z$
Appendix 4-2: Supplementary data for Taguchi L₉ analyses

(i)  **Estimated factor effects on surface roughness, Rₐ, S/N ratio**

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### Estimated factor effects on resultant machining forces, $F_m$, S/N ratio

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### Variables
- Feed: X
- Depth of cut (DoC): ±
- Speed (RPM): +
### (iii) Estimated factor effects on tool life, TL, S/N ratio

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<th>DoC (mm)</th>
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Notes: + indicates a positive factor effect on tool life.
Appendix 5-1: Effects of machining at different fibre orientation on tool wear growth for cutting speed of 190 m/min (5,000 RPM) and feed rate of 0.24 mm/rev.
Appendix 5-2: SEM micrographs of worn cutting tool for various machining parameters

$v = 190 \text{ m/min}, f_r = 0.24 \text{ mm/rev and } A = 45^\circ$

$v = 230 \text{ m/min}, f_r = 0.32 \text{ mm/rev and } A = 90^\circ$

$v = 150 \text{ m/min}, f_r = 0.24 \text{ mm/rev and } A = 90^\circ$
Appendix 5-3: Regression output for Taylor’s tool life equation generated from Microsoft Excel Data Analysis Toolbox

Table 1: Regression output for tool life, TL without fibre orientation

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<tr>
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<tr>
<td>Standard Error</td>
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ANOVA

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<th>MS</th>
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<th>Significance F</th>
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Coefficients

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Note: df: Degree of freedom, SS: sum of square error, MS: variance, $F$: Fisher statistics

Table 2: Regression output for tool life, TL with fibre orientation

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ANOVA

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Coefficients

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Note: df: Degree of freedom, SS: sum of square error, MS: variance, $F$: Fisher statistics
Appendix 5-4: Supplementary predicted data from Eqs. 5.4-5.5 for the tested parameters

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Average 5.17 13.08

Feed rate, $f_r = 0.16$ mm/rev

Feed rate, $f_r = 0.32$ mm/rev
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<th>Orientation (°)</th>
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Average

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Average of % Error for Eqs. 5.4 and 5.5 = 15.98%
Appendix 5-5: Supplementary results on repeated experiments at the specified machining parameters

![Graph 1](image1)

- **Tool wear vs time**
- \(v = 150\ \text{m/min}, \ f_r = 0.24\ \text{mm/rev}\)

![Graph 2](image2)

- **Tool wear vs time**
- \(v = 190\ \text{m/min}, \ f_r = 0.24\ \text{mm/rev}\)
Tool wear vs time

($v = 230$ m/min, $f_r = 0.24$ mm/rev)

Trial 1
Trial 2
Trial 3
Appendix 5-6: Supplementary results of machining force variations

Feed rate, $f_r = 0.16$ mm/rev

Feed rate, $f_r = 0.32$ mm/rev

Variations of feed force, $F_x$ and cutting forces, $F_y$ with respect to changing feed rates and cutting speeds
Variations of feed force, $F_x$ and cutting forces, $F_y$ with respect to changing feed rates and cutting speeds
Appendix 5-7: Regression outputs for tool wear-machining forces regression analyses generated from Microsoft Excel Data Analysis Toolbox

Table 3: Summary regression output for tool wear-feed force relationship

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Table 4: Summary regression output for tool wear-feed force relationship

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<td>V</td>
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<td>F</td>
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<td>F_y</td>
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Appendix 5-8: Normal probability plots from regression analyses

Normal probability plot of residuals for regression output of Eq. 5.8

Normal probability plot of residuals for regression output of Eq. 5.9
Appendix 5-9: Supplementary results of MRA predicted versus experimental data for selected machining parameters

\[ v = 190 \text{ m/min}, f_r = 0.24 \text{ mm/rev} \]

\[ v = 170 \text{ m/min}, f_r = 0.24 \text{ mm/rev} \]
$v = 150 \text{ m/min}, f_r = 0.24 \text{ mm/rev}$

$\nu = 170 \text{ m/min}, f_r = 0.24 \text{ mm/rev}$
Appendix 6-1: Generated fuzzy rules from ANFIS models

**ANFIS_Fy:**

1. If (Cutting Speed is HIGH) and (Feed Rate is MEDIUM) and (Feed Force is CLUSTER1) then (out1 is out1cluster1) (1)
2. If (Cutting Speed is HIGH) and (Feed Rate is MEDIUM) and (Feed Force is CLUSTER2) then (out1 is out1cluster2) (1)
3. If (Cutting Speed is LOWEST) and (Feed Rate is LOW) and (Feed Force is CLUSTER3) then (out1 is out1cluster3) (1)
4. If (Cutting Speed is HIGHEST) and (Feed Rate is HIGH) and (Feed Force is CLUSTER4) then (out1 is out1cluster4) (1)
5. If (Cutting Speed is HIGH) and (Feed Rate is MEDIUM) and (Feed Force is CLUSTER5) then (out1 is out1cluster5) (1)
6. If (Cutting Speed is LOW) and (Feed Rate is LOW) and (Feed Force is CLUSTER6) then (out1 is out1cluster6) (1)
7. If (Cutting Speed is LOW) and (Feed Rate is MEDIUM) and (Feed Force is CLUSTER7) then (out1 is out1cluster7) (1)
8. If (Cutting Speed is LOWEST) and (Feed Rate is HIGH) and (Feed Force is CLUSTER8) then (out1 is out1cluster8) (1)
9. If (Cutting Speed is HIGH) and (Feed Rate is MEDIUM) and (Feed Force is CLUSTER9) then (out1 is out1cluster9) (1)

**ANFIS_Fz:**

1. If (Spindle Speed is in1cluster1) and (Feed Rate is in2cluster1) and (Cutting Force is in3cluster1) then (out1 is out1cluster1) (1)
2. If (Spindle Speed is in1cluster2) and (Feed Rate is in2cluster2) and (Cutting Force is in3cluster2) then (out1 is out1cluster2) (1)
3. If (Spindle Speed is in1cluster3) and (Feed Rate is in2cluster3) and (Cutting Force is in3cluster3) then (out1 is out1cluster3) (1)
4. If (Spindle Speed is in1cluster4) and (Feed Rate is in2cluster4) and (Cutting Force is in3cluster4) then (out1 is out1cluster4) (1)
5. If (Spindle Speed is in1cluster5) and (Feed Rate is in2cluster5) and (Cutting Force is in3cluster5) then (out1 is out1cluster5) (1)
6. If (Spindle Speed is in1cluster6) and (Feed Rate is in2cluster6) and (Cutting Force is in3cluster6) then (out1 is out1cluster6) (1)
7. If (Spindle Speed is in1cluster7) and (Feed Rate is in2cluster7) and (Cutting Force is in3cluster7) then (out1 is out1cluster7) (1)
8. If (Spindle Speed is in1cluster8) and (Feed Rate is in2cluster8) and (Cutting Force is in3cluster8) then (out1 is out1cluster8) (1)
9. If (Spindle Speed is in1cluster9) and (Feed Rate is in2cluster9) and (Cutting Force is in3cluster9) then (out1 is out1cluster9) (1)
10. If (Spindle Speed is in1cluster10) and (Feed Rate is in2cluster10) and (Cutting Force is in3cluster10) then (out1 is out1cluster10) (1)
11. If (Spindle Speed is in1cluster11) and (Feed Rate is in2cluster11) and (Cutting Force is in3cluster11) then (out1 is out1cluster11) (1)
12. If (Spindle Speed is in1cluster12) and (Feed Rate is in2cluster12) and (Cutting Force is in3cluster12) then (out1 is out1cluster12) (1)
Appendix 6-2: Final Gaussian MFs after ANFIS training
Appendix 6-3: Supplementary results of checking datasets

[Graph 1: Cutting Force vs. Tool Wear]

- **Cutting Force (N),**
- **Tool Wear (mm),**
- **s = 170 m/min, f = 0.24 mm/rev**

[Graph 2: Feed Force vs. Tool Wear]

- **Feed force (N),**
- **Tool wear (mm),**
- **v = 150 m/min, f = 0.24 mm/rev**
Appendix 7-1: Static images of chip formation

Machining parameters: $s = 500$ RPM, $f_r = 0.32$ mm/rev and fibre orientation, $90^\circ$
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