



Faculty of Manufacturing Engineering

**MACHINING PARAMETERS AND TOOL GEOMETRY
OPTIMIZATION FOR TRIMMING COMPOSITE LAMINATES
USING RESPONSE SURFACE METHODOLOGY**

اونيورسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Syahrul Azwan bin Sundi @ Suandi

Doctor of Philosophy

2021

**MACHINING PARAMETERS AND TOOL GEOMETRY OPTIMIZATION
FOR TRIMMING COMPOSITE LAMINATES USING RESPONSE SURFACE
METHODOLOGY**

SYAHRUL AZWAN BIN SUNDI @ SUANDI



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2021

DECLARATION

I declare that this thesis entitled “Machining Parameters and Tool Geometry Optimization for Trimming Composite Laminates using Response Surface Methodology” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.



Signature :

Name : Syahrul Azwan bin Sundi @ Suandi

Date : 15 / 05 / 2021

اونيورسيتي تيمكين ماليزيا ملاك

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Doctor of Philosophy in Manufacturing Engineering.

Signature
Supervisor Name Associate Professor Dr. Raja Izamshah Bin Raja Abdullah
Date 20 / 05 / 2021

اونيورسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

DEDICATION

To my beloved parents,
family and all my supportive friends.



ABSTRACT

In recent years, carbon fiber-reinforced polymer (CFRP) materials have gained tremendous attention from industries, especially in the aerospace industry due to their properties such as high strength-to-weight ratio and high corrosion resistance. In general, composite materials are usually manufactured in a near-net shape. Hence, secondary processes such as trimming, drilling and countersinking are usually applied to obtain the final desired dimension. Composite behavior such as its inhomogeneity, anisotropy, and interaction with the cutting tool becomes challenging for the manufacturers. Matrix cracking, un-cut fibers, fibers pull-out, and burned matrices are the typical problems or damages that arise during the machining process which may contribute to the rejection of parts. Moreover, the abrasive nature of the reinforcement fibers of the composite materials induces rapid wear rate to the cutting tool during machining which finally impacted the overall manufacturing cost. Therefore, this present study aims to determine an optimum tool geometry for a router tool-type (the number of teeth and the helix angles) and the optimized machining parameters in minimizing workpiece damages during the trimming of CFRP material. The trimming performances evaluated include the trimmed surface roughness in the longitudinal and transverse direction as well as the cutting force. Surface roughness evaluation was done by utilizing the portable surface roughness while cutting force was measured using the piezoelectric-dynamometer. Besides, further qualitative observation on the trimmed surface quality, and the effect on the tool wear, were performed using an optical microscope and a 3-Dimensional (3D) surface topography imager. The design of experiment (DOE-Taguchi and Response Surface Method-RSM) is the primary method deployed in the overall research's milestones. Through the statistical analysis, the machining parameters (cutting speed, V_c , and feed per tooth, f_z) resulted in a more significant effect on the surface roughness and the cutting force value than the selected tool geometry. On the other hand, considering only the tool geometry, the most predominant factor that affected the trimmed surface quality was the number of teeth on the left side, followed by the helix angle and the number of teeth on the right side. The relationship for each mentioned response, namely, the surface roughness (in the longitudinal and transverse direction) and the cutting force associated with the tool geometry, was successfully established using statistical model analysis. The optimum tool geometry (the combination of the number of teeth on the left and the right side respectively; 12, 8 and the helix angle; 24°) and the machining parameters (the cutting speed, V_c 118.47 m/min and the feed per tooth, f_z 0.05 mm/rev) were chosen based on the highest desirability score. The new optimum router tool geometry was fabricated and a validation experimental work was performed which finally confirmed its validity by obtaining the relative error between the predicted and the experimented data less than 10%. Ultimately, the main aim of the present study which was to determine an optimum tool geometry for a router tool-type geometry that can accommodate the trimming results, namely minimum surface roughness (the longitudinal and transverse direction), the cutting force and the tool wear has been successfully achieved.

**PENGOPTIMUMAN PARAMETER PEMESINAN DAN GEOMETRI PERKAKAS
UNTUK PEMOTONGAN KOMPOSIT BERLAPIS MENGGUNAKAN METODOLOGI
PERMUKAAN SAMBUTAN**

ABSTRAK

Ke belakang ini, bahan polimer yang diperkuat dengan serat karbon (CFRP) mendapat perhatian luar biasa oleh industri, terutamanya industri aeroangkasa disebabkan oleh sifat bahannya seperti nisbah kekuatan kepada berat yang tinggi dan ketahanan kakisan. Secara amnya, bahan komposit diperbuat kepada rupabentuk yang hampir. Oleh itu, proses sekunder seperti pemotongan, penggerudian dan pembenaman biasanya digunakan untuk mendapatkan dimensi akhir yang diinginkan. Tingkah laku komposit seperti ketidaksamaan, anisotropi dan interaksi dengan perkakas menjadikan tugas yang mencabar bagi pengeluar. Keretakan matriks, serat yang tidak dipotong, serat yang ditarik keluar dan matriks terbakar merupakan antara permasalahan umum atau kerosakan yang berlaku semasa proses pemesinan yang boleh menyebabkan penolakan bahan tersebut. Selain itu, sifat serat tetulang yang kasar pada bahan komposit tersebut mampu mempercepatkan kadar kehausan kepada perkakas semasa proses pemesinan seterusnya mengakibatkan peningkatan kos. Oleh itu, kajian ini bertujuan untuk menentukan geometri perkakas yang optimum (jumlah gigi dan sudut heliks) serta parameter pemesinan yang optimum dalam meminimalkan kerosakan benda kerja semasa pemotongan bahan CFRP. Analisa pemesinan yang dinilai merangkumi kekasaran permukaan pada arah menegak dan melintang serta daya pemotongan. Penilaian kekasaran permukaan dilakukan dengan menggunakan kekasaran permukaan mudah alih sementara daya pemotong diukur dengan menggunakan piezoelectric-dynamometer. Selain itu, analisa kualitatif lebih lanjut mengenai kualiti permukaan serta kehausan kepada perkakas dilakukan dengan menggunakan mikroskop optik dan pencitraan topografi permukaan 3-Dimensi (3D). Reka bentuk eksperimen (DOE-Taguchi dan Response Surface Method-RSM) adalah kaedah utama yang digunakan dalam pencapaian keseluruhan penyelidikan. Merujuk kepada analisis statistik, parameter pemesinan (kelajuan pemotongan, V_c , dan suapan per gigi, f_z) menunjukkan kesan yang lebih ketara pada kekasaran permukaan dan nilai daya pemotongan daripada geometri perkakas yang dipilih. Sebaliknya, faktor yang paling ketara mempengaruhi kualiti permukaan yang dipotong adalah bilangan gigi di sebelah kiri diikuti dengan sudut heliks dan jumlah gigi di sebelah kanan. Hubungan untuk setiap tindak balas, iaitu kekasaran permukaan pada kedua-dua arah dan daya pemotongan yang berkaitan dengan geometri perkakas, dihubungkan dengan menggunakan analisis model statistik. Geometri perkakas optimum (gabungan bilangan gigi kiri dan kanan masing-masing; 12, 8 dan sudut heliks; 24°) dan parameter pemesinan (kelajuan pemotongan, V_c 118.47 m/min dan suapan per gigi, f_z 0.05 mm/rev) dipilih berdasarkan skor keinginan tertinggi. Perkakas dengan geometri optimum tadi kemudiannya difabrikasi dan divalidasi dengan eksperimen yang akhirnya ditentukan dengan ralat relatif diantara data yang diramal dan yang sebenar adalah kurang daripada 10%. Kesimpulannya, objektif utama kajian ini iaitu menentukan geometri perkakas yang optimum dalam meminimalkan kekasaran permukaan, daya pemotongan dan kehausan perkakas telah dapat dicapai dengan jayanya.

ACKNOWLEDGEMENTS

In the Name of Allah, the Most Gracious, the Most Merciful

My profound gratitude goes to Almighty Allah (SWT), the Great and the Most Beneficent, all praise and glory are to Him alone for endowing me the wisdom, knowledge, health, time, resources, and opportunity to see this dream a reality. I would like to extend my appreciation to the Universiti Teknikal Malaysia Melaka (UTeM) and the Malaysian Ministry of Higher Education (MOHE) to provide the research platform and financial assistance.

Special thank goes to my principal supervisor, Associate Professor Dr. Raja Izamshah bin Raja Abdullah for his valuable guidance, constructive comments, and careful reading to shape this thesis into its final form. Sincere appreciation also goes to my co-supervisors, Associate Professor Dr. Mohd Shahir bin Kasim for his advice and assistance. My heartfelt thanks to Managements of Aerospace Composite Malaysia (ACM) Sdn. Bhd., Mr. Khairul Aswat bin Abdullah (Senior Manager of Innovation and Technology Department) for the great teamwork we had, especially on the optimization projects of the cutting tool technology and the CAD/CAM tool paths. Our success was the motivation for this study. I am also indebted to my beloved colleagues and friends for their words of wisdom and encouragement during my study. I would have long given up this dream if it weren't for all of you behind me, cheering and lifting my spirit.

Finally, from the bottom of my heart, I am grateful to my beloved wife, Intan Sharhida binti Othman, for her encouragement and who has been the pillar of strength in all my endeavors. My eternal love also to all my children, Muhammad Muizzuddin Qayyum, Muhammad Hafiyuddin Hasif, Muhammad Waqiyuddin Wafiy, Muhammad Izzuddin Mishary and Nur Aafiyah Insyirah for their patience and understanding. I would also like to thank my beloved parents (Hj. Suandi bin Alang Ahmad and Hjh. Siti Mariam binti Ahmad) for their endless support, love, and prayers. Finally, thank you to all the individual(s) who had provided me the assistance, support, and inspiration to embark on my study.

TABLE OF CONTENTS

	PAGE
DECLARATION	i
APPROVAL	ii
DEDICATION	iii
ABSTRACT	vi
ABSTRAK	ix
ACKNOWLEDGEMENTS	xvi
LIST OF TABLES	xviii
LIST OF FIGURES	xix
LIST OF APPENDICES	xix
LIST OF ABBREVIATIONS	xix
LIST OF PUBLICATIONS	xix
CHAPTER	1
1. INTRODUCTION	1
1.1 Background	1
1.2 Problem statement	3
1.2.1 Challenges in machining composite materials	3
1.2.2 Damages in machining composite materials	5
1.2.3 Tool geometry	6
1.3 Research objectives	7
1.4 Research significance	9
1.5 Scope of research	9
1.6 Structure of thesis	10
2. LITERATURE REVIEW	13
2.1 Composite material	13
2.2 Overview on CFRP	18
2.2.1 Fiber forms/architecture	18
2.2.2 Laminated/stacked composite	20
2.3 Trimming of CFRP material	21
2.3.1 Types of cutting tool for trimming CFRP material	22
2.3.2 Manufacturing/grinding processes of solid rod cutting tools	25
2.4 Effects of Tool geometry in trimming of CFRP materials	27
2.5 Surface Roughness	45
2.6 Cutting Forces	54
2.7 Tool Wear	58
2.8 Review of Statistical Techniques used in machining	63
2.8.1 Taguchi Method	63
2.8.2 Response Surface Methodology	64
2.9 Summary of literature review	68
3. RESEARCH METHODOLOGY	70
3.1 Workpiece material	73
3.2 Cutting tool (router) details	75
3.2.1 Phase 1: Preliminary study of various router tool geometry and trimming parameters	77

3.2.2	Phase 2: Optimization of router tool geometry and trimming parameters	81
3.2.3	Phase 3: Validation process of the model based on the optimized value of the tool geometry	86
3.3	Test and analysis equipment and procedure	87
3.3.1	Machine tool	87
3.3.2	Tool holding	88
3.3.3	Trimming fixture	89
3.4	Cutting strategy	90
3.5	Surfaces quality evaluations	91
3.5.1	Surface roughness analysis, Ra	91
3.5.2	Optical microscopy imaging	93
3.5.3	3D surface topography	95
3.6	Cutting forces measurement	96
3.7	Experimental design and statistical analysis	98
3.7.1	Taguchi Experimental Design	99
3.7.2	Response Surface Methodology (RSM)	103
3.7.3	Optimization with Central Composite Design (CCD) technique	107
3.7.4	Multiple Response Optimizations Result	109
3.8	Scope of research methodology	111
4.	RESULTS AND DISCUSSION	113
4.1	Phase 1: Preliminary study of various router tool geometry and trimming parameters	114
4.1.1	Result of Preliminary Study (Phase 1)	114
4.1.2	Microscopy Observation	121
4.2	Phase 2: Optimization of router tool geometry and trimming parameters	127
4.2.1	Longitudinal Surface Roughness RSM result and analysis	127
4.2.2	Transverse Surface Roughness RSM result and analysis	142
4.2.3	Resultant Force RSM result and analysis	160
4.2.4	Microscopy Observation	174
4.2.5	Summary of Taguchi and RSM Analysis	184
4.2.6	Multiple Responses Optimization	185
4.3	Phase 3: Validation process of the model based on the optimized value of the tool geometry	190
4.3.1	Validation Process	190
4.3.2	Summary of Multiple Response Optimizations Analysis	195
5.	CONCLUSION	196
5.1	Conclusions	196
5.2	Contribution to Knowledge	200
5.3	Recommendations for Future Work	200
	REFERENCES	202
	APPENDICES	214

LIST OF TABLES

TABLE	TITLE	PAGE
2.1	Increased use of fiber-reinforced polymer composites in aircraft structures (Rana and Figueiro, 2016)	14
2.2	Summary of the effect on tool geometry by previous researchers in trimming of CFRP material	42
2.3	Summary of the effect on the surface roughness by previous researchers in trimming of CFRP material	51
2.4	Summary of the effect on the cutting forces by previous researchers during trimming of CFRP material	56
2.5	Summary of the effect on tool wear by previous researchers in trimming of CFRP material	61
2.6	Adaptation of DOE by previous researchers in trimming of CFRP material	66
3.1	CFRP details	74
3.2	CFRP properties	74
3.3	CFRP stacking direction configuration	75
3.4	Factors and level	78
3.5	Router geometrical details	79
3.6	Taguchi L27 experimental matrix	80
3.7	Factors and levels for RSM (CCD)	82

3.8	Customization of router / burrs tool geometries	82
3.9	RSM-CCD Matrix	84
3.10	Haas GR-510 CNC specification	87
3.11	Standard Parameter of S/N ratio (Source: Manual of Design Experiment)	102
3.12	L27 orthogonal array for thirteen (13) factors and three (3) levels (313)	102
3.13	Coded values of 50 runs of experiments by applying RSM - CCD	108
4.1	Preliminary result on averaged surface roughness (μm)	117
4.2	Overall result of surface roughness (μm)	118
4.3	Averaged result for the longitudinal surface roughness	129
4.4	Overall result for the longitudinal surface roughness	131
4.5	ANOVA table for longitudinal surface roughness	134
4.6	Averaged result for the transverse surface roughness	144
4.7	Overall result for the transverse surface roughness	146
4.8	ANOVA table for transverse surface roughness	149
4.9	Result for the resultant force	162
4.10	ANOVA Table for resultant force	165
4.11	Details geometry of T4 (R4), T9 (R34) and T14 (R38)	176
4.12	Goal and constraint for the factors and responses	187
4.13	Multiple responses optimization solutions	188
4.14	Result of the validation data on the longitudinal surface roughness, Ra	191
4.15	Result of the validation data with percentage (%) of relative error on the longitudinal surface roughness, Ra	191
4.16	Result of the validation data on the transverse surface roughness, Ra	192

4.17	Result of the validation data with percentage (%) of relative error on the transverse surface roughness, Ra	193
4.18	Result of the validation data with percentage (%) of relative error for the resultant force	194



LIST OF FIGURES

FIGURE	TITLE	PAGE
1.1	Use of composites in the Boeing 787 (Rana and Fanguero, 2016)	2
1.2	Factors affecting trimming quality of CFRP material	4
1.3	Common damages in machining CFRP materials (Hashish, 2013)	6
1.4	Fundamental formula in determining machining parameters (Sandvik-Coromant, 2012; Kalpakjian, 2014)	7
2.1	Increased growth of composite use in aircrafts over the years (Brown, 2014)	14
2.2	History of CFRP introduction to Airbus aircraft (Breuer, 2016)	15
2.3	Basic building blocks in fiber-reinforced composites (Mallick, 2018)	16
2.4	Classification of composite materials based on reinforcement and matrix types (Fridlyander and Marshall, 1998)	18
2.5	Types of woven fabrics (a) plain weave (low drape-ability/high crimp); (b) satin weave (good drape-ability/low crimp); and (c) twill weave (average drape-ability/average crimp) (Hexcel, 2013)	20
2.6	Types of laminated/stacked composite; Uni-directional (UD)-Left; Multi-directional-Right (Rana and Fanguero, 2016)	21
2.7	Comparison between peripheral/edge and end milling (Sheikh-Ahmad, 2009)	22

2.8	Advanced tool design for composites machining (courtesy of Seco Tool)	23
2.9	PCD Tool (courtesy of Guhring KG)	24
2.10	Helical helix end mill geometry (courtesy of Sandvik Coromant)	24
2.11	Burr/router tool (courtesy of OSG) and details of geometrical features	25
2.12	Overall processes in cutting tool fabrication for solid rod type	27
2.13	a) Coarse grit diamond abrasive b) fine grit diamond abrasive c) carbide with 10° helix angle d) PCD with 10° helix angle e) PCD with 30° helix angle (Colligan and Ramulu, 1992)	28
2.14	Geometry and characteristics of PCD cutters (El-Hofy et al., 2011)	29
2.15	Staggered PCD cutter details geometry (Chen et al., 2017)	30
2.16	(a) Two (2) straight-flutes (2SF), (b) Two (2) helix-flutes (2HF), (c) Four (4) serrated straight-flutes (4SSF), and (d) Details of the grooves design of 4SSF tool (Nguyen-dinh et al., 2020)	30
2.17	(a) Two-flute helical helix end mill (helix angle; 30°, rake angle; 10°/30°, clearance angle; 9°), (b) Six-flute straight/ 0° helix angle end mill (Davim and Reis, 2005)	31
2.18	Details of cutting tools' geometry and the analyzed milling paths (Uhlmann et al., 2016)	31
2.19	DLC coated of normal and high-helix end mills with the specific helix angles (β) (Hosokawa et al., 2014)	32
2.20	(a) Details of vertical and incline milling positions, (b) 2-4-6 flutes helical helix end mill tools (Can, 2017)	33
2.21	(a) right hand edge and left hand edge helical helix tool, (b) newly proposed tool; left-right edge helical helix tool (Wang et al., 2020)	33

2.22	(a) Three (3)-flutes PCD tool (b) 12-flutes multiple teeth/burr (CVD coated) tool (c) Three (3)-flutes PCD tool (Duboust et al., 2017)	34
2.23	Comparative study on the effect of coatings, micro grain, cobalt content and multi-tooth versus PCD tool (López de Lacalle et al., 2009)	35
2.24	Details of the investigated cutting tools (T1, T2 & T3) (Prakash et al., 2016)	36
2.25	(a) Burr tool (tungsten carbide) (b) Burr tool (diamond coated tungsten carbide) (c) Four-flute helical helix end mill (diamond coated) (Haddad et al., 2013)	37
2.26	Details burr tool geometries: a) fine grain, b) medium grain, c) coarse grain (Gara and Tsoumarev, 2016)	38
2.27	Types of cutting tools and their details specification (Sheikh-Ahmad et al., 2018)	39
2.28	Details of the tool geometries and the trimmed surfaces topographical results (Ashworth et al., 2019)	40
2.29	(a) Multi-tooth/burr tool geometry; (b) Up-down/compression router tool (Cunningham et al., 2018)	41
2.30	(a) Ø11.138 mm double point angle twist drill (by Seco) (b) Ø10 (mm) burr tool (by Seco); c) Ø10 mm burr tool (coarse tooth by Fraisa) and (d) Ø10 mm burr tool (medium tooth by Fraisa); (e) Ø10 mm helical helix end mill (by Tivoly) (Geier and Pereszlai, 2020)	41
2.31	SEM Images of trimmed surfaces CFRP (Haddad et al., 2014)	47
2.32	Flank wear, chipping and catastrophic failure (ISO 8688-2)	58
3.1	Flow of the overall research	72
3.2	CFRP panel dimensions	74

3.3	(a) End mill – helical spiral; (b) router/burr type; (c) compression router type; (d) PCD insert type	76
3.4	Details geometrical features of router tool	78
3.5	General router tool geometrical specification	79
3.6	Three different geometrical feature of router tool; (a) Type 1 (fine), (b) Type 2 (medium) and (c) Type 3 (smooth)	79
3.7	Overall processes in cutting tool fabrication and validation procedure	86
3.8	Haas GR-510 CNC machine	87
3.9	Tool holder used during the trimming process and the tool overhang always maintained at 40 mm	88
3.10	(a) CAD view of the jig with CFRP plate, (b) final fixture assembly preparation	90
3.11	Details of surface roughness measurement procedure applied	92
3.12	Stylus self-calibration of SJ-410 roughness tester	93
3.13	Surface roughness evaluation setup	93
3.14	Nikon MM-800 is utilized to further observe the trimmed surface	94
3.15	Nikon MM-800 is also utilized to observe the tool wear	95
3.16	3D surface topography microscope (Olympus OLS5000)	96
3.17	Schematic diagram on the apparatus setup for the cutting forces	97
3.18	Kistler piezoelectric dynamometer Type 9257B	98
3.19	Sample graph of the acquired forces signal from DynoWare software	98
3.20	Type of response surface a) maximum b) plateau c) maximum outside the experimental region d) minimum e) saddle (Almeida et al., 2008)	106
3.21	Response surface design of CCD (Montgomery, 2009)	107
4.1	Result of longitudinal surface roughness, Ra for all 27 runs	116

4.2	Main effects plot for SN ratio of surface roughness	120
4.3	Photomicrographs (<i>at magnification of 300 μm</i>) taken by optical microscope on the trimmed surfaces exhibiting the closed-up conditions of the trimmed surfaces	122
4.4	Enlarged of photomicrographs taken on the trimmed surface for various machining conditions; R2 (top) and R19 (bottom)	123
4.5	Overall cutting-edge condition taken by optical microscopy (<i>at magnification of 300 μm</i>)	125
4.6	Enlarged of photomicrographs taken on the cutting edge condition of R2, R6, R9 and R24	126
4.7	(a) View of fractured tooth from clearance face (b) Flank wear in fractured teeth (Janardhan, 2005; Janardhan et al., 2006)	126
4.8	R37 details geometry (a - 20° helix angle and number of teeth 10; 10); R38 details geometry (b - 35° helix angle and number of teeth 10; 10)	132
4.9	Plotted data of the surface roughness result in longitudinal direction	133
4.10	Longitudinal surface roughness (a) Normal plot of residuals; (b) Predicted vs actual	136
4.11	3D response surface between the longitudinal surface roughness, Ra (μm) and the number of teeth-LEFT & RIGHT at the helix angle; a) 24° b) 28° c) 32°	139
4.12	Importance of the left number of teeth in comparison to the right number of teeth during trimming operation	140
4.13	3D response surface of longitudinal surface roughness, Ra (μm) with the machining parameters (cutting speed, V_c and feed per tooth, f_z)	141

4.14	R37 details geometry (a - 20° helix angle and number of teeth 10; 10) ; R38 details geometry (b-3 5° helix angle and number of teeth 10; 10)	147
4.15	Plotted data of the surface roughness result in transverse direction	148
4.16	Transverse surface roughness: (a) Normal plot of residuals; (b) Predicted vs actual	151
4.17	3D response surface between the transverse surface roughness, Ra (μm) and the number of teeth-LEFT & RIGHT at the helix angle; a) 24° b) 28° c) 32°	154
4.18	Actual photos of the tool geometries details; left representing 24° and right representing 32° of helix angle	155
4.19	Influence of helix angle on the chip evacuation process (for better illustration, standard end mill geometry has been used to describe the effect of helix angle)	155
4.20	The engagement point of the cutting tool and the CFRP specimen panel	156
4.21	3D surface topography for T1, T2, T8 and T14	158
4.22	3D response surface of transverse surface roughness, Ra (μm) with the machining parameters (cutting speed, V_c and feed per tooth, f_z)	160
4.23	Plotted data of the resultant force, F_r result	164
4.24	Resultant force, F_r : (a) Normal plot of residuals; (b) Predicted vs actual	167
4.25	3D response surface of resultant force, F_r (N) between the number of teeth-LEFT & RIGHT and at the helix angle; a) 24° b) 28° c) 32°	170
4.26	The effect of the number of teeth on the gap/clearance between the teeth	171
4.27	Details of 3D surface topography for T15 (R40)	172

4.28	3D response surface of resultant force, F_r (N) with the machining parameters (cutting speed, V_c and feed per tooth, f_z)	174
4.29	Significant photomicrographs taken by the optical microscope on the trimmed surfaces	177
4.30	Enlarged photomicrographs of T4-R4 (top), T10-R34 (middle) and T14-R38 (bottom)	178
4.31	An interfacial rupture occurs between the fiber and the matrix (left); due the intensity of the force increases changed fibers orientation caused uncut and pulled-out of fibers (right) (Gara and Tsoumarev, 2017b)	179
4.32	Micrographs of the tool wear observation on the cutting edge	182
4.33	Enlarged micrographs on the cutting edge of the most significant tool geometries to indicate the types of wear occurred	183
4.34	Tool wear observations for three different grains of burr tool type (Gara, et al., 2017)	184
4.35	Ramp function graph for the optimization	188
4.36	Details of the optimized tool design	189
4.37	Comparison result of the longitudinal surface roughness on the actual validation data and the predicted data	192
4.38	Comparison result of the transverse surface roughness on the actual validation data and the predicted data	193
4.39	Comparison result of the resultant force, F_r on the actual validation data and the predicted data	194

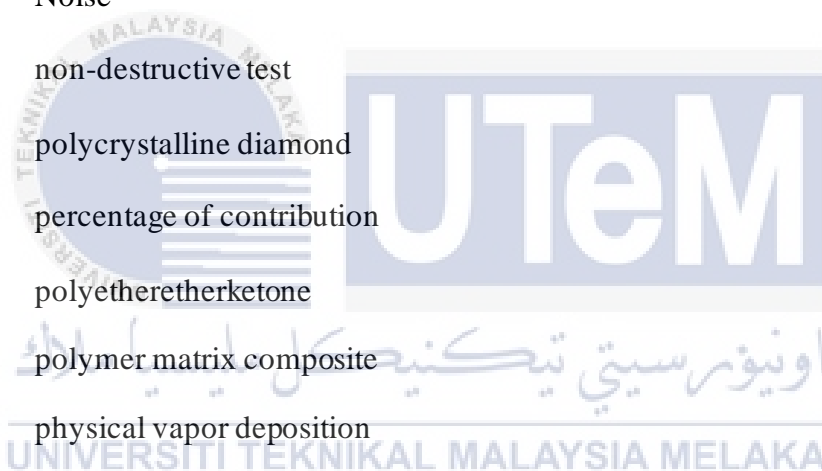
LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Detail drawing of trimming fixture used for the trimming process – Figure 3.10	215
B	Acknowledgement letter from ACM for the industrial attachment	218
C	Appointment letter from ACM Sdn. Bhd.	219
D	Seminar on Machining of Composite Materials (Invited Speaker)	220
E	Photos with ACM's Engineers	221
F	Copyright document of the optimized tool geometry	222
G	Innovations Awards	223
H	Letter of Intent (LOI) from Gandtrack Asia Sdn Bhd	227

LIST OF ABBREVIATIONS

ANOVA	-	analysis of variance
AWJ	-	abrasive water jet machining
CA	-	chilled air
CBN	-	cubic boron nitride
CFRP	-	carbon fiber reinforced plastic composite
CMC	-	ceramic matrix composite
CNC	-	computer numerical control
CTE	-	coefficient of thermal expansion
CVD	-	chemical vapor deposition
DLC	-	diamond liked carbon
EHM	-	equivalent homogenous material
FEA	-	finite element analysis
FRP	-	fiber reinforced polymer composite
GFRP	-	glass fiber reinforced plastic composite
HAZ	-	heat affected zone
HLU	-	hand lay-up
HSM	-	high speed machining
HSS	-	high speed steel
HV	-	hardness Vickers
IR	-	infra-red

ISO	-	international standard organization
LPI	-	liquid phase impregnation
MD	-	multi-directional
MIS	-	manufacturing instruction sheet
MMC	-	metal matrix composite
MQL	-	minimum quantity lubrication
MS	-	mean square
MSDS	-	material safety data sheet
MSE	-	mean square of error
N	-	Noise
NDT	-	non-destructive test
PCD	-	polycrystalline diamond
PCR	-	percentage of contribution
PEEK	-	polyetheretherketone
PMC	-	polymer matrix composite
PVD	-	physical vapor deposition
RMS	-	root mean square
SEM	-	scanning electron microscopy
SS	-	sum of square
SST	-	sum of square total
UAM	-	ultrasonic assisted machining
UD	-	unidirectional
UHM	-	ultra-high modulus
WC	-	tungsten carbide



LIST OF PUBLICATIONS

Indexed Journal with Impact Factor

1. **Sundi, S.A.**, Izamshah, R., Kasim, M.S., 2020. Effect of Machining Parameters on Surface Roughness in Edge Trimming of Carbon Fiber Reinforced Plastics (CFRP). *Tribology Online*, 15 (2), pp. 53-59. (Scopus indexed, Q2, IF = 0.38 (2019))
2. **Sundi, S.A.**, Izamshah, R., Kasim, M.S., S.Ding and M.F Jaafar, 2020. Statistical Analysis on the Effect of Machining Conditions towards Surface Finish during Edge rimming of Carbon Fiber Reinforced Plastics (CFRP). *International Journal of Nanoelectronics and Materials (IJNEAM)*, 13 (Special Issue), pp. 199-210. (Scopus indexed, Q3, IF = 0.22 (2019))
3. R. Izamshah, **S.A. Suandi**, M. Akmal, M. F. Jaafar, M.S. Kasim, S. Ding, M.H Hassan, 2020. Experimental and Numerical Investigation on the Role of Double Helical Angle Tool in Trimming CFRP Aerospace Composites. *International Journal of Nanoelectronics and Materials (IJNEAM)*, 13 (Special Issue), pp. 379-392. (Scopus indexed, Q3, IF = 0.22 (2019))

Conference Proceedings

1. **Sundi, S.A.**, Izamshah, R., Kasim, M.S. and Abdullah, M.K.A, 2019. Effect of machining parameters on surface quality during edge trimming of multi-directional CFRP material: Taguchi method. *IOP Conference Series: Materials Science and Engineering*, 469 (1), 012095. <https://doi.org/10.1088/1757-899X/469/1/012095>
2. **Sundi, S.A.**, Izamshah, R., Kasim, M.S., Amin, A.T.M. and Kumaran, T., 2019. Influence of Router Tool Geometry on Surface Finish in Edge Trimming of Multi-Directional CFRP Material. *IOP Conference Series: Materials Science and*