Mechanical Performance and Machinability of Hybrid FRP Composite Via Abrasive Water-Jet Machining using Response Surface Methodology and Numerical Model

by

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DEDICATION

To:

My Dearest Parents,

Mr. Wong King Hock & Mrs. Lau Wu Hee

My Handsomest Eldest Brother and Lovely Sister in Law and Niece,

Wong Kiing Aik, Lau Lu Fei and Yilia Wong

My Pretties Sister and Handsome Brother in Law

Winnie Wong and Chieng Leh Yong

My Handsomest Younger Brothers,

Wong Kiing Seng and Wong Kiing Ing

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LIST OF ABBREVIATIONS

FRP	Fibre-Reinforced Polymer
AWJM	Abrasive Water-Jet Machining
DOE	Design of Experiment
RSM	Responses Surface Methodology
ANOVA	Analysis of Variance
SPH	Smoothed Particle Hydrodynamic
FEA	Finite Element Analysis
CMC	Ceramic Matrix Composites
MMC	Metal Matrix Composites
PMC	Polymer Matrix Composites
ROM	Rule of Mixture
LBM	Laser Beam Machining
EDM	Electric Discharge Machining
CNC	Computer Numerical Control
MRR	Material Removal Rate
HAZ	Heat Affected Zone
SOD	Stand Off Distance
CFD	Computational Fluid Dynamic
CA	Cellular Automata
WJ	Water-Jet
ALE	Arbitrary Lagrangian Eulerian
VARTM	Vacuum Assisted Resin Transfer Molding
RTM	Resin Transfer Moulding
ASTM	American Society for Testing and Materials
UTM	Universal Testing Machining
SEM	Scanning Electron Microscopy

EDX	Energy Dispersive X-ray
FCD	Face-Centred Composite Design
CMM	Coordinate Measuring Machine
PI	Prediction Internal
VUMAT	User-Defined Material Behaviour Subroutine

LIST OF SYMBOLS

P_h	Hydraulic Pressure
Ra	Average Arithmetic Surface Roughness
$\dot{m}_A$	Abrasive Flow Rate
V_f	Traverse Rate
M_i	Initial Mass of Specimen
M_{cr}	Remain Mass of the Fibre Reinforcement
M_f	Final Mass of Specimen
V_r	Volume Fraction of Specimen
R	Rate of Crosshead Motion
Z	Rate of Straining of Outer Fibre
L	Support Span of Spacemen
d	Depth of Beam
T_R	Kerf Ratio
W_t	Top Kerf Width
W_b	Bottom Kerf Width
F_d	Delamination Factor
W_{max}	Maximum Width of Delamination area
W	Actual Width of Cut
R^2	Coefficient of Determination
V_A	Abrasive Velocity
ρ_W	Water Density
Ω	Domain
m^B	Mass of particle B
ρ^B	Density of particle B
F_{fib}^T	Tensile loads fibre damage

F_{fib}^{C}	Compressive loads fibre damage
ε_{11}^{OT}	Failure initiation for tension
ε_{11}^{OC}	Failure initiation for compression
E_{11}	Longitudinal elastic modulus
d_{fib}	Damage parameter of fibre
d_{11}^{T}	Tensile fibre-dominated damage parameter
ε_{11}	Current strain
ε_{11}^{FT}	Tensile failure strain
X^{T}	Longitudinal tensile strengths
l_{fib}	Corresponding characteristic length

Prestasi Mekanikal dan Kebolehmesinan Komposit Polimer Bertetulang Gentian Hibrid dengan Menggunakan Pemesinan Jet Air-Bahan Lelas dengan Kaedah Permukaan Sambutan dan Model Berangka

ABSTRAK

Atas dorongan ke atas keperluan peralatan dan komponen yang menggunakan bahan lebih ringan dan kuat di dalam sektor penerbangan dan automotif, aktiviti penyelidikan untuk mencapai keperluan ini telah membangun dengan pesat. Kajian di dalam tesis ini adalah satu penyiasatan eksperimen mengenai pemotongan komposit polimer bertetulang gentian hibrid (FRP) dengan menggunakan pemesinan jet air-bahan lelas (AWJM). Sebelum proses pemesinan ini dijalankan, bahan rencam polimer bertetulang gentian hybrid dihasilkan di dalam pelbagai bentuk atau susunan rekaan menggunakan pemindahan damar pengacuan-vakum bagi tujuan penyaringan. Sifat mekanikal seperti kekuatan tegangan, kekuatan lenturan dan pecahan isipadu komposit hibrid ditentukan mengikut piawaian ASTM. Hasil penyaringan menunjukkan bahawa susunan $[CW_2]_6$ lebih unggul dari segi sifat mekanik, di mana C dan W adalah merupakan gentian karbon dan gentian kaca. Berdasarkan prestasi mekanikalnya yang cemerlang, keboleh-mesinan bahan rencam polimer bertetulang gentian hibrid $[CW_2]_6$ ini kemudiannya dikaji dengan lebih lanjut. Walaubagaimanapun, diketahui bahawa pemesinan bahan rencam FRP tanpa sebarang kerosakan adalah amat mencabar apabila menggunakan proses pemesinan konvensional. Hal ini disebabkan sifat tidak isotropik, keheterogenan, kepekaan termal, dan sangat lelas bahan rencam tersebut. Kajian secara komprehensif untuk menilai keberkesanan dan kombinasi parameter optimum pemesinan AWJ dengan nisbah *kerf*, kekasaran permukaan dan *delamination* (lapisan permukaan dan bawah) pada bahan rencam ini telah dijalankan dengan kaedah permukaan sambutan dan analisis varians. Reka bentuk faktorial 2^k yang mengikuti reka bentuk komposit berpusat (FCD) dengan sejumlah 30 eksperimen (16 titik faktorial-2^4, lapan mata paksi-2^4, dan enam mata pusat) digeriskan menggunakan perisian *Design Expert*. Hasil kajian dengan jelas telah menunjukkan bahawa pemotongan komposit ini adalah amat mencabar kerana penghasilan tirus *kerf* yang buruk, permukaan kasar dan *delamination* teruk di bahagian atas dan bawah permukaan yang dipotong. Keputusan analisa juga menunjukkan nisbah *kerf* dipengaruhi oleh jarak *stand-off* dan kadar terabas. Selain itu, kedua-dua bahagian *delamination* dipengaruhi oleh kadar aliran bahan lelas, kadar terabas, dan tekanan hidraulik. Kualiti permukaan terjejas oleh kadar aliran bahan lelas, jarak *stand-off*, kadar terabas dan tekanan hidraulik. Kesimpulannya, dengan meningkatkan tenaga kinetik aliran jet-air bahan lelas (pada kelajuan yang rendah) dapat mengurangkan nisbah *kerf*, kekasaran pemukaan dan *delamination*. Penentuan parameter proses optimum dalam mencapai komposit berkualiti tinggi selepas proses pemesinan berada pada kadar aliran kasar 600 g/min, tekanan hidraulic 262.6 MPa, Jarak pendirian 2 mm dan kelajuan rendah melepasi 1000 mm/min. Dengan demikian, penyelidikan selanjutnya adalah untuk memahami mekanisme kerosakan permukaan di dalam keadaan laju tinggi AWJM melalui kaedah unsur terhingga serta zarah hidrodinamik lancar. Keputusan menunjukkan bahawa genangan zarah bahan lelas di titik impak menghasilkan retakan dan perambatan *delamination* dan seterusnya mekanisme ricihan. Persetujuan yang baik antara simulasi dan hasil eksperimen dari segi kualitatif dan kuantitatif telah dibuktikan melalui kajian khusus ini.

Mechanical Performance and Machinability of Hybrid FRP Composite Via Abrasive Water-Jet Machining using Response Surface Methodology and Numerical Model

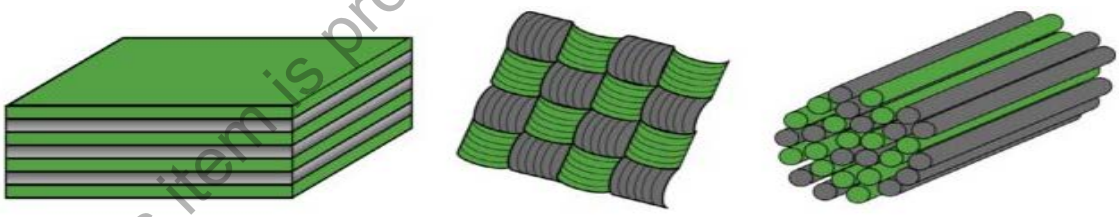
ABSTRACT

Driven by the need for light-weight and high-strength materials for parts and components in the aviation and automotive sectors, research activities in attaining these requirements have been exponentially increased. This research describes an experimental investigation on the machinability of hybrid fibre reinforcement polymer (FRP) composites under abrasive water-jet machining (AWJM). Prior to machining, hybrid FRP composites of different architectures or arrangements were initially fabricated using resin transfer moulding for screening purposes. Mechanical properties such as tensile strength, flexural strength and volume fraction of the hybrid composites were determined per ASTM standards. Material screening experimentation indicates that the $[CW_2]_6$ arrangement, where C and W are weaved carbon fibre and glass fibre respectively, were superior in terms of mechanical properties. The machinability of $[CW_2]_6$ hybrid composites was then further investigated due to their excellent mechanical performance. However, it is well known that machining of FRP composites without any defect is extremely challenging when using conventional machining processes. This is mainly due to their inherent anisotropic, heterogeneous, thermal sensitivity, and highly abrasive of nature of fibre reinforcements. This research attempted to comprehensively evaluate the significant and optimal combination of AWJ machining parameters with respect to the kerf ratio, surface roughness and delamination (entrance and exit) on the hybrid FRP composite by the response surface methodology and statistical analysis of variance. A 2^k factorial design that follows a face-centred composite design (FCD) with a total of 30 experimental runs (16 factorial points—2^4, eight axial points—2×4, and six centre points) were outlined using Design Expert software. It is worth to note here that previous attempts in the trimming of composites has been challenging due to the presence of poor kerf taper, rough surface and severe delamination on top and bottom surface of trimmed surface. Experimental results revealed that the kerf ratio was influenced by the stand-off distance and traverse rate. On the other hand, both side of delamination were only influenced by abrasive flow rate, traverse rate, and hydraulic pressure. Lastly, surface quality was highly affected by the abrasive flow rate, stand-off distance, and traverse rate rather than the hydraulic pressure. In short, minimum kerf ratio, surface roughness, and delamination can be achieved by increasing the kinetic energy of abrasive water-jet stream when impinging into the composite under a lower speed. The optimum process parameters setting in achieving high-quality composites after the machining process were at abrasive flow rate of 600 g/min, hydraulic pressure of 262.6 MPa, stand-off distance of 2 mm and low traverse speed of 1000 mm/min. Further work on understanding the mechanism of surface damage under high velocity condition of AWJM has been developed using finite element method coupled with smooth-particle hydrodynamics. Results of this numerical model indicated that stagnation of abrasive particles at impact point generated delamination (crack initiation and propagation) and subsequently shear-out mechanisms. A good agreement was evident (qualitatively and quantitatively) between the simulation and experimental results in this particular study.

CHAPTER 1 : INTRODUCTION

1.1 Background

Hybrid fibre-reinforced polymer composites are extensively and exclusively developed in recent years through combination of two different fibre types in several distinct configurations. As depicted in Figure 1.1, hybrid fibre reinforced composites can be classified into interply, intraply, intimately mixed hybrid, and other configuration types (Kretsis, 1987; Zhang et al., 2012). Each configuration has its own unique advantages that relatively depend upon composite design structures and load expectations. Interply or intraply configurations are often designed to compose of low and high elongation fibres of different types. As claimed by Dong et al. (2013) and Swolfs et al.(2014), the primary purpose of hybridising these fibres is to synergising the superiority and moderating the shortcomings of individual fibres.



(a) (b) (c)

Figure 1.1 Hybrid composite configurations: (a) interply, (b) intraply, and (c) intimately mixed (Swolfs et al., 2014)

Fabrication of non-hybrid and hybrid fibre-reinforced polymer composites (FRP) typically involves combining, compacting, and processing the reinforcing fibres with polymer matrices. The fabrication processes or steps can be rather time-consuming and care intensive, which results in a substantial processing cost. Thus, they are typically produced to near-net shapes, through one of the following processes; namely, wet hand

lay-up, resin transfer moulding, and autoclave manufacturing. Despite the near-net shape process, final finishing processes which involve machining and cutting operations are essential to achieve any intricate shape requirements, critical part dimensions, and other functional needs, so that their subsequent manufacturing applications can be met. These applications include military equipment, aerospace component (e.g. wings, fuselages and tails), automotive transportation (e.g. luxury car bodies), sporting goods (e.g. badminton rackets and bicycle frames), and various other industrial applications.

Over the years, fundamental experimental studies on mechanical performance of carbon or glass FRP composites have attracted a significant attention of researchers worldwide. The primary interest of the research is to develop composites with improved performance to be qualified for the use in a broad spectrum of applications, particularly for high-performance aerospace and automotive components. However, the primary drawback of typical carbon fibre composites is their low compressive-to-tensile strength ratio, which can hinder mechanical performance (Dong et al., 2013). Likewise, glass fibre composites lack of high modulus-to-weight ratio property. In light of these drawbacks, hybrid FRP composites are developed to maintain superiority and overcome the moderate shortcomings of individual fibre types.

As aforementioned, the finishing processes through machining operations remain essential and are governed by a few important requirements. These include meeting tight dimensional, shape, and functional requirements. Trimming or machining operations are typically encountered during the early or first stage of manufacturing plan to bring the FRP composites into their desired and final form prior to assembly. Therefore, high quality and reliability requirements of FRP composites are of ultimate importance. This is due to the high cost of rework processes and discarding of damaged pieces. In addition,