Experimental and Analytical Study of Drilling Hybrid Glass/Carbon Fibre Reinforced Epoxy Composite

By

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DEDICATION

To My Lovely Parents and Sibling

Tan Peng Teong, Father

Chen Yoke Mooi, Mother

Tan Chia Yong, Eldest Sister

Tan Yan Ling, Younger Sister

Tan Yong Sin, Brother

Lim Wooi Eng, Fiancé

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LIST OF ABBREVIATIONS

FRP	Fibre-Reinforced Polymer
VARTM	Vacuum Assisted Resin Transfer Molding
ROM	Rule of Mixture
ANOVA	Analysis of Variance
ROHM	Rule of Hybrid Mixture
RSM	Responses Surface Methodology
PAN	Poly-Acrylo-Nitrile
PMC	Polymer Matrix Composites
MMC	Metal Matrix Composites
CMC	Ceramic Matrix Composites
PEEK	Poly Ether-Ether Ketone
DGEBA	Diglycidyl Ether of Bisphenol A
RTM	Resin Transfer Moulding
WC	Tungsten Carbide
LEFM	Linear Elastic Fracture Mechanics
PCD	Polycrystalline Diamond
HSS	High-Speed Steel

CNC	Computer Numerical Control
TiC	Titanium Carbide
ASTM	American Society for Testing and Materials
SEM	Scanning Electron Microscopy
DOF	Degree Of Freedom
MRR	Material Removal Rate
MAPE	Mean Absolute Percentage Error

LIST OF SYMBOLS

D	Drill Bit Diameter
X	Tool Displacement
a	Crack Size
h	Uncut Thickness
H	Workpiece Thickness
G	Critical Energy Release Rate
k_p	Peeling Factor
E	Young's Modulus
v	Poisson Ratio
ξ	Proportional Coefficient of Resultant Force to Drilling Thrust Force
M_i	Initial Mass of Specimen
M_f	Final Mass of Specimen
ρ_c	Density of Specimen
ρ_f	Density of Fibre Reinforcement
σ_h	Tensile/ Flexural Strength for Hybrid Composites
σ_C	Tensile/ Flexural Strength for Carbon Fibre Composites
σ_G	Tensile/Flexural Strength of Glass Fibre Composite
V	Volume Fraction.
λ_c	Hybrid Effect
F_x	Feed Force
F_y	Cutting Force

F_z	Thrust Force
S/N	Signal-to-Noise Ratio
F_d	Delamination Factor
D_{max}	Maximum Diameter of Damaged Hole
Do	Hole Actual Diameter
Ra	Average Arithmetic Surface Roughness
σ_{St}	Specific Strength
σ_t	Ultimate Tensile Strength
SS	Sum of Square
f	feed rate in mm/min
V	Spindle Speed in RPM
$\tilde{\eta}$	Total Mean of S/N Ratio
η_j	Means *S/N* Ratio at Optimum Level
K	Stress Concentration Factor
β_i	Coefficient of Main Factors
β_{ii}	Square or Interaction Coefficients
δW	Virtual External Work
δU	Virtual Strain Energy
δQ	Virtual Surface Energy
D_{ij}	Bending Stiffness

Eksperimen dan Analisis Terhadap Penggerudian Gentian Hibrid Komposit Polimer

ABSTRAK

Pada masa kini, komposit hibrid telah menjadi semakin menarik dalam sektor penyelidikan dan pembangunan disebabkan mempunyai ciri-ciri mekanikal yang boleh difabrikasi berdasarkan spesifikasi yang dikehendaki. Kajian tentang pemprosesan, pembangunan dan pengujian komposit hibrid yang dibuat daripada matriks logam, sintetik atau bahan semula jadi telah diadakan. Namun begitu, beberapa masalah masih timbul dalam proses pembuatan, terutamanya dalam pemesinan seperti penggerudian bahan-bahan berlamina. Hakikatnya, gentian adalah bersifat *anisotropic*, kekurangan deformasi plastik dan kasar, merupakan cabaran yang besar dalam pemesinan komposit hibrid. Berdasarkan kajian sebelum ini, kerosakkan dalam penggerudian akan menyebabkan penolakan yang tinggi (60 %) dalam proses pemasangan. Oleh sebab itu, kajian penyelidikan ini melanjutkan pengetahuan asas dalam penggerudian gentian hibrid komposit (FRP) dengan kaedah eksperimen dan analitikal. Sebelum ujian penggerudian eksperimen, penilaian prestasi mekanikal hibrid FRP komposit telah dijalankan. Secara khususnya, kesan hibrid terhadap komposit karbon dan gentian kaca dalam matriks polimer *epoxy* telah dinilai dengan kaedah eksperimen. Kesimpulannya, sifat-sifat fizikal dan mekanikal monolitik komposit telah dipertingkatkan 48 % dengan campuran karbon FRP dalam komposit kaca FRP. Di samping itu, analisis secara teori melalui *Rule of Mixture* menunjukkan bahawa komposit hibrid FRP mempunyai kesan positif dari segi tegangan dan lenturan. Walaupun teknologi fabrikasi bagi komposit hibrid FRP semakin maju dalam proses pengeluaran komponen hampir bentuk sempurna, akan tetapi, pemesinan sekundar masih diperlukan untuk mencapai ukuran yang ditetapkan. Oleh itu, parametrik yang optimum untuk mengurangkan kesan *delamination* dan kekasaran permukaan telah ditentukan dengan kaedah *Taguchi* dan analisis statistik. Keputusan eksperimen menunjukkan bahawa prestasi penggerudian lebih banyak dipengaruhi oleh suapan dan geometri mata gerudi yang direka khas (67 %), berbanding dengan kelajuan putaran mata gerudi (18 %). Perubahan dalam suapan disebabkan faktor peningkatan daya tujah semasa proses penggerudian. Oleh yang demikian, untuk mencapai penggerudian yang berkualiti tanpa menjejaskan prestasi mata gerudi dan kadar pengeluaran, parametrik penggerudian pada kelajuan putaran mata gerudi 7500 RPM, 0.08 mm/rev suapan dan *Step drill* telah dicadangkan dalam kajian ini. Walaupun hasil kajian parametrik menunjukkan bahawa parametrik penggerudian yang diingini boleh mengurangkan *delamination*; perubahan dalam daya tujah diketahui memainkan peranan yang penting dalam mempengaruhi saiz *delamination*. Justeru, kajian seterusnya adalah untuk memahami mekanisme penggerudian yang menyebabkan kesan *delamination* melalui kaedah analisis. Tujuan utama model ini adalah untuk mengira daya tujah kritikal pada permulaan *delamination* semasa proses penggerudian. Hasil kajian analisis ini menunjukkan bahawa kerosakkan delamination boleh dielakkan jika daya tujahan dalam penggerudian adalah lebih rendah daripada nilai kritikal daya tujah, 47.64 N. Anggaran daya tujah kritikal didapati selari dengan daya tujah yang didapati dalam kajian ini. Oleh itu, model ini boleh menjadi penanda aras atau rujukan kepada industri untuk mengurangkan kerosakkan *delamination* dan meningkatkan prestasi komposit hibrid FRP yang digerudi dalam proses pemasangan.

Experimental and Analytical Study of Drilling Hybrid Fibre Reinforced Polymer Matrix Composite

ABSTRACT

Hybrid composites have become increasingly attractive in research and development activities in recent times due to the capabilities to tailor their mechanical performance or characteristics to specific needs. Current research and innovation in the field of hybrid composites include processing, development and testing of metal matrix hybrid composites as well as the synthetic and natural fibre hybrid composites. Nonetheless, a number of complications arise in the manufacturing processes, particularly in machining such as drilling, of these multiphase laminated materials. The fact is that machining of composites or hybrid composites presents a great challenge due to anisotropic nature of the material, lack of plastic deformation and abrasiveness of the fibre reinforcements. According to the previous statistic studies, unqualified holes leads to approximately 60 % part rejections during the final assembly process. Therefore, this research study pursues an experimental and analytical approaches to extend the fundamental knowledge in drilling hybrid fibre reinforced polymer (FRP) composites. Prior to the drilling tests, the evaluations of the mechanical performance of hybrid FRP composite have been attempted. Specifically, the hybrid effect of the plain woven carbon and E-glass fibres hybrid composites within an epoxy polymer matrix was experimentally evaluated. It was evident that the physical properties and mechanical strength of monolithic fibres composite were enhanced 48 % by hybridising carbon fibres into the glass FRP composites. In addition, theoretical analysis through the rule of mixture reveals that the hybrid FRP composites have exhibited a positive hybrid effect in term of tensile and flexural behaviors. Even though fabrication technology for the hybrid FRP composites has well advanced in the production of near-net shape components, the secondary machining process is vital for completing the post-manufactured of these materials. Thus, the desired setting for minimising the delamination damage and surface roughness were determined using the Taguchi methodology and statistical analyses. The results reveal that these drilling responses were strongly influenced by the feed and the specially designed tool geometries (67 %) rather than the spindle rotational speed (below 18 %). Changes in the feed are likely to attribute to the increase of the thrust force and strain rate during the drilling process. Therefore, for achieving high-quality holes without compromising the tool life and production rate, the optimum parameters suggested were at the middle range spindle speed (7500 RPM), low feed (0.08 mm/rev) and low point angle (Step drill). While results of the parametric study showed that the desired drilling parameters are feasible for minimization of delamination damage; the changing in the thrust force is known to play a critical role in influencing the size of delamination zone. Thus, further work on understanding the mechanism of drilling-induced delamination through analytical approach is inevitable. The main purpose of the model is to compute the critical thrust force at the onset of delamination during the drilling process. Results of this analytical study indicate that the delamination damage can be prevented or avoided if the applied thrust force is lower than the thrust force critical value, 47.64 N. A good agreement between the estimated critical thrust force and the measured thrust force was evident in this particular study. It is important to note that this model can be an attractive benchmark or reference for industrial practice in reducing delamination damage for better assembly performance of the drilled hybrid FRP composites.