UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Manufacturing Engineering

LASER MACHINING OF GLASS FIBRE REINFORCED PLASTICS (GFRP)

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LASER MACHINING OF GLASS FIBRE REINFORCED PLASTICS (GFRP)

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A thesis submitted
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DECLARATION

I declare that this thesis entitled “Laser Machining of Glass Fibre Reinforced Plastics (GFRP)” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is concurrently submitted in candidature of any other degree.

Signature : …………………………….
Name : …………………………….
Date : …………………………….

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 for the award of Master of Science in Manufacturing Engineering.

Signature : ………………………………………..
Supervisor Name : ………………………………………..
Date : ………………………………………..

DEDICATION

This thesis is dedicated to my father,

Late Kolandaisamy Manuel

May his memory forever be a comfort and a blessing.

To my beloved mother,

Arulmary Savarimuthu

for all support that you have given to me.

For my wife,

Nitthiya Palani

whom never give up in supporting and encouraging me.

ABSTRACT

Glass fibre reinforced plastics (GFRP) composite materials are in increasingly high demand, particularly in marine industries for reduced weight. This is due to their superior structural characteristics (in fatigue and static conditions) as well as light weight. Anisotropic and heterogeneous features of these materials, however, have posed serious challenges in machining of GFRP. Hence, a new machining technology needs to be investigated. Laser is a non-contact process which is identified as being satisfactory for this research project. A major quality challenge in terms of the laser cutting quality of these materials includes dimensional accuracy. Various laser parameters and cutting techniques are investigated in this study to minimise these defects. In order to improve the cutting quality and dimensional accuracy, design parameters and responses were correlated, modelled, analysed, optimized and experimentally validated to meet the requirements of marine engineering sponsored industry. The objective of this research work is to study the different aspects of GFRP composite cutting using CO_2 laser and to establish the relationship between the kerf width, taper and roundness with the process parameters like laser power, cutting speed, gas pressure, frequency and duty cycle. The experimental plans were conducted according to the design of experiment (DOE) to accommodate a full range of experimental analysis. Identification of the important parameter effects presented using analysis of variance (ANOVA) technique combined with graphical representation provides a clearer picture of the whole laser profiling phenomenon. The results show that, the interaction between lower level laser power (2600 Watt), higher level cutting speed (1200 mm/min), higher level gas pressure (8 Bar), medium level frequency (1825 Hz) and medium level duty cycle (96 %) gives better cutting performance towards three responses. Finally, the predictive mathematical model that was established to predict the responses were also validated and are found to be promising in resolving the cut quality issues of industrial GFRP laminates with the error value 16.12 % for kerf width, 18.60 % for taper and 16.28 % for roundness. It was demonstrated that, the response surface methodology (RSM) has played a valuable role to identify the interaction factors of design parameters in attaining industrial desired cut quality response.

ABSTRAK

Permintaan untuk "glass fibre reinforced plastics" (GFRP) adalah semakin meningkat, terutama di industri marin untuk mengurangkan berat. Ini adalah disebabkan ciri-ciri struktur yang kukuh (dalam keadaan lesu and statik) serta ringan. Walaupun bahan ini mempunyai ciri-ciri anisotropik and heterogen, tetapi menimbulkan cabaran serius dalam permesinan GFRP. Maka teknologi permesinan yang baru hendaklah disiasat. Laser merupakan satu proses tanpa sentuh telah dikenalpasti untuk projek ini. Ketepatan dimensi merupakan cabaran utama dalam kualiti pemotongan laser. Pelbagai pembolehubah laser and teknik pemotongan disiasat dalam kajian ini untuk mengurangkan kecacatan. Pembolehubah laser dan tindakbalas dihubungkait, dimodel, dianalisis, dioptimum dan disahkan menerusi eksperimen untuk memperbaiki kualiti pemotongan dan ketepatan dimensi bagi memenuhi keperluan industri marin. Objektif penyelidikan ini adalah untuk mengkaji aspek pemotongan GFRP komposit dengan menggunakan CO_2 *laser dan menunjukkan interaksi diantara "kerf width", "taper" and "roundness" dengan pembolehubah seperti kuasa laser, kelajuan pemotongan, tekanan gas, frekuensi dan "duty cycle". Eksperimen dikendalikan dengan mengunakan teknik "design of experiments" (DOE) bagi manampung keseluruhan analisis kajian. Kesan pembolehubah yang signifikan dikenalpastikan dengan menggunakan teknik "analysis of variance" (ANOVA) bersama dengan persembahan graf bagi memberikan gambaran yang jelas keseluruhan fenomena. Keputusan menunjukkan bahawa interaksi antara kuasa laser (2600 Watt) pada tahap rendah, kelajuan pemotongan (1200 mm/min) pada tahap tinggi, tekanan gas (8 Bar) pada tahap tinggi, frekuensi (1825 Hz) pada tahap sederhana dan "duty cycle" (96 %) pada tahap sederhana dapat memberi pretasi pemotongan yang baik. Akhirnya, formula matematik untuk ramalan yang dihasilkan telah disahkan dan didapati mampu menyelesaikan isu kualiti potongan lamina GFRP dengan nilai ralat 16.12 % bagi "kerf width", 18.60 % bagi "taper" dan 16.28 % bagi "roundness". Ia ditunjukkan bahawa, "response surface methodology" (RSM) telah memainkan peranan yang penting dalam mengenal pasti faktor interaksi pembolehubah dalam mencapai kualiti yang baik seperti kehendak industri.*

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATION

µm	-	Micron
%	-	Percentage
3D	-	Three dimensional
ANOVA	-	Analysis of variance
AWJ	-	Abrasive waterjet
CCD	-	Central composite design
CFRP	-	Carbon fibre reinforced plastics
CMC	-	Ceramic matrix composites
CMM	-	Coordinate measuring machine
CNC	-	Computer numerical control
CO_2	-	Carbon dioxide
DF	-	Desirability function
DOE	-	Design of experiments
ECM	-	Electrochemical machining
EDM	-	Electrical discharge machining
EWR	-	Electrode wear rate
FRP	-	Fibre reinforced plastics
GA	-	Genetic algorithm
GFRP	-	Glass fibre reinforced plastics
GPa	-	Gigapascal
HAZ	-	Heat affected zone
He	-	Helium
HRC	-	Hardness Rockwell C
Hz	-	Hertz
Kg/m^3	-	Kilogram per cubic meter
kW	-	Kilowatt
MDF	-	Medium-density fibreboard

mm - Millimetre
mm/min - Millimeters per minutes
MMC - Metal matrix composites
MMNC - Metal matrix nano-composite
MMR - Material removal rate
MPa - Megapascal
N_2 - Nitrogen
Nd:YAG - Neodymium – doped yttrium aluminium garnet
Nd:YV04 - Neodymium – doped yttrium ortovanadate
Nm - nanometer
OC - Optical comparator
PMC - Polymer matrix composites
Ra - Surface roughness
RSM - Response surface methodology
Sdn. Bhd. - Sendirian berhad
SEM - Scanning electron microscope
SOD - Stand-off distance
USM - Ultrasonic machining
W - Watt
WEDM - Wire electric discharge machine
YB:YAG - Ytterbium – doped yttrium aluminium garnet

LIST OF PUBLICATIONS

1. Sivarao, **Robert, K.M.**, Sivakumar, D., Taufik, Yuhazri, Tan, C.F., Ian, H., Alif, and Tin, S.L., 2012. An Exploratory Study - Critical Laser Processing of Composite Materials. *International Journal of Engineering Research & Technology,* 1 (10), pp.1 - 8. (DOAJ Indexed)

2. Sivarao, S., **Milkey, K.R**., Samsudin, A.R., Dubey, A.K., and Kidd, P., 2013. RSM Modelling and Optimization of CO2 Laser Machining of Industrial PVC Foam. *International Review on Modelling and Simulations,* 6 (4), pp.1339 - 1343. (SCOPUS Indexed)

3. Sivaraos, **Milkey, K.R**., Samsudin, A.R., Dubey, A.K., and Kidd, P., 2013. Taguchi Modeling and Optimization of Laser Processing in Machining of Substantial Industrial PVC Foam. *International Journal of Applied Engineering Research,* 8 (12), pp.1415 - 1426. (SCOPUS Indexed)

4. Sivaraos, **Milkey, K.R**., Samsudin, A.R., Dubey, A.K., and Kidd, P., 2014. Comparison Between Taguchi Method and Response Surface Methodology (RSM) in Modelling CO2 Laser Machining. *Jordan Journal of Mechanical and Industrial Engineering,* 8 (1), pp.35 - 42. (SCOPUS Indexed)

CHAPTER 1

INTRODUCTION

This chapter describes the background of the research and explains briefly the problem statements, objectives and scope of this research. This chapter also includes the organization of the thesis report.

1.1 Background

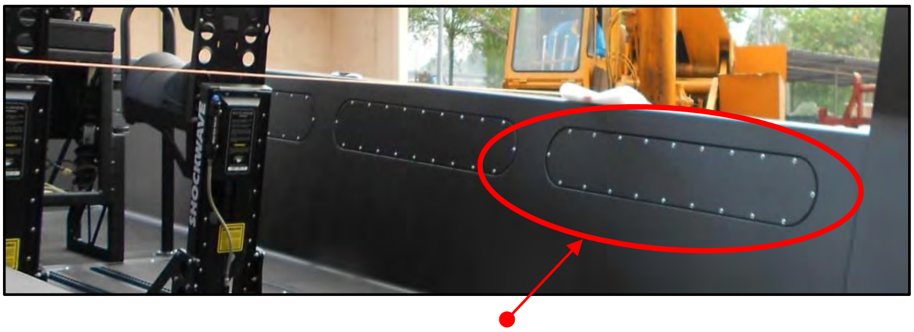
The use of fibre reinforced composite materials in marine and aerospace industries has grown considerably in recent years because of their unique properties such as high specific stiffness and strength, high damping, good corrosive resistance and low thermal expansion (Matthews and Rawling, 1999). Generally machining of composites is very different in comparison to other materials. This is due to the inhomogeneous and anisotropic properties of these structures. The machining challenges are particularly experienced in the case of composites because of high difference between mechanical and thermal properties of the constituents.

In terms of structural application, the joining of composite laminates to other material structures using bolted joints is unavoidable. Besides, the performance of the product is mainly dependant on surface quality and dimensional accuracy of the machined hole. Although composites components are produced to near-net shape, further machining process is often needed to fulfil the requirements related to tolerances of assembly needs.

The material anisotropy resulting from fibre reinforcement considerably influences the quality of the machined hole. Hence, precise machining needs to be performed to ensure the dimensional stability and interface quality.

In fact, composite materials are being used more widely in the construction of marine structures than ever before. Figure 1.1 shows the P38 craft and the part name called blender is used as function of storage purpose for the weapons which installed into sides of the cockpit. Used in various parts of a patrol craft, the result is a far lighter boat that can achieve a higher rate of speed than the same type of boat constructed of aluminium or steel. In additionally, the lighter weight keeps fuel costs down and that a significant savings for a boat that may hold hundreds or even thousands of gallons of fuel.

(a) P38 High Speed Craft (Anonymous, 2014a)



(a) Blender

Figure 1.1 P38 Craft and Blender Position

1.2 Problem Statement

Machining glass fibre reinforced plastics (GFRP) has always represented a big challenge due to their anisotropic and heterogeneous behaviour. The process of machining GFRP has been identified difficult in the needs to avoid creating fibre pull-out, delamination, and poor surface quality may affect part performance. Additionally, an inability to meet dimensional tolerances may require secondary rework, or even part rejections. Similarly, UES International Sdn. Bhd. also faces numerous challenges to produce the GFRP without going through secondary process which not only requires additional cost, but also a high variation in dimensional accuracy. There were a lots of problems such as fibre pull-out, delamination, etc., when the GFRP was processed using twist drills and these weaken the entire structure in real life applications as shown in Figure 1.2. On the other hand, Abrasive waterjet (AWJ) also has been tried to avoid this problem, but ended up with localised stress concentration which causes mechanical destruction to the GFRP that weakens hole surrounding as illustrated in Figure 1.3. To certain extend, they have also tried laser cutting but in a very traditional approach which ended-up in unsatisfactory results. Knowing where, laser processing is highly potential to provide good solution in hole making of GFRP, a scientific approach is to be formulated to investigate systematically with elements involving modelling, optimization, and validation in order to provide the industry with high cut quality outcome.

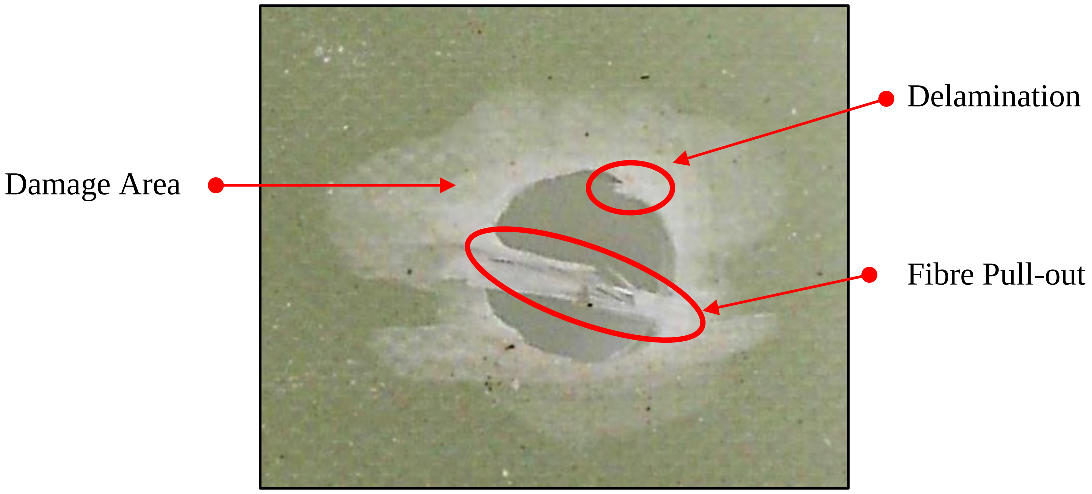


Figure 1.2 Results from Conventional Drilling

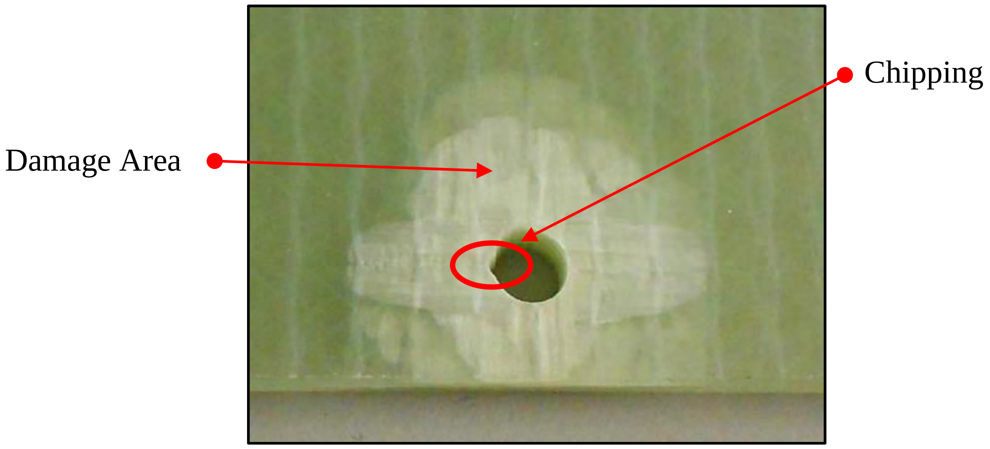


Figure 1.3 Results from Abrasive Waterjet

1.3 Research Objectives

The objectives of this industrial based research work are to:

a) Investigate the correlation of laser processing parameters and GFRP materials.

b) Model, analyse and optimize the laser processing parameters by using response surface methodology (RSM).

c) Experimentally validate the model of processing GFRP.

1.4 Research Scope

This research work relies within the scope of below stated condition:

a) The machine used was LVD Helius 2513 Laser Cutting Machine.

b) Five selected design parameters were cutting speed, duty cycle, gas pressure, frequency and laser power.

c) The GFRP work material thickness was 4 mm.

d) Commercially available Design Expert 7.0 software was used for the purpose of data analysis and modelling.

e) The quality responses that measured were the kerf width, taper and roundness.

1.5 Thesis Organization

This thesis is organized into five chapters. Chapter one introduces the research background which includes the problem statement, objectives and scopes. Chapter two reviews the literature related to laser machining, composite materials, machining of composites, modelling and cut quality characteristics. Chapter three describes the methodological aspects which includes materials selection, processing, observation, analysis, modelling and validation. Chapter four presents the results and discussion of the experiment, while final chapter provides conclusions, and recommendation for future research.

CHAPTER 2

LITERATURE REVIEW

This chapter deals with literature review related to laser machining, composite materials, common machining of composites, cutting quality characteristic and modelling by RSM. All the information in this chapter was used as a reference and guidance to complete this research.

2.1 Laser Machining

Lasers are capable of generating high power laser beams with high beam quality which are suitable for cutting, drilling, welding and other applications. The carbon dioxide (CO_2) and neodymium – doped yttrium aluminium garnet (Nd:YAG) laser are the two laser technologies have been the workhorse in multiple material processing applications for several decades. Laser-active medium in a CO_2 laser is a combination of CO_2, nitrogen (N_2) and helium (He) gases, where CO_2 is the laser-active molecule where CO_2 laser emits the infrared laser radiation with a wavelength of 10.6 µm and possess overall efficiencies of approximately 10 to 13 % claims Charschan (1993).

Ion (2005) has written that the stimulation of the laser-active medium is accomplished by electrical discharge in the gas. During the stimulation process, the nitrogen molecules transfer energy from the electron impact to the CO_2 molecules. The transition from energetically excited CO_2 molecules (upper vibration level) to a lower energy level (lower vibration level) is accompanied by photon release thus leading to the emission of a laser beam. The CO_2 molecules return to the ground state by colliding with the helium atoms which comprise a major share of the gas mixture, and the CO_2 molecules in the ground state are then available for another cycle.

The CO_2 laser and Nd:YAG laser which reach an output power range of 2 to 20 kW respectively will then be available for cutting applications (Anonymous, 2014b). In general, there are two approaches for the hole making process, namely, laser drilling and laser cutting.

2.1.1 Laser Drilling

In laser drilling applications, a focused laser beam is used as a heat source that increases temperature rapidly to the melting and evaporation temperature of the substrate material. The erosion front at the bottom of the drilled hole propagates in the direction of the line source in order to remove the material (Chryssolouris, 1991). The advantages of laser drilling include the ability to drill holes in difficult-to-machine materials such as super-alloys, ceramics, and composites without high tool wear rate and is normally associated with conventional machining of these materials (Voisey and Clyne, 2004). In general, there are three approaches to laser drilling, namely, single pulse, percussion, and trepanning as shown in Figure 2.1 (Verhoeven, 2004).

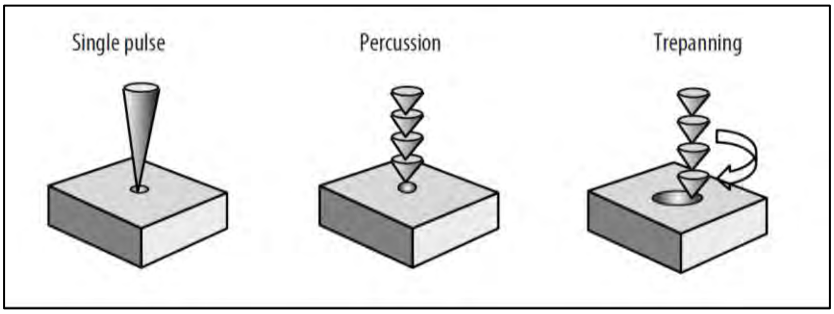


Figure 2.1 Different Approaches of Drilling (Steen and Mazumder, 2010)