OPTIMIZATION OF CUTTING PARAMETERS OF SUGAR PALM FIBER-REINFORCED UNSATURATED POLYESTER COMPOSITE WITH LASER BEAM AND ABRASIVE WATER JET CUTTING TECHNOLOGIES

By

FATHI ALUHISHI MUFTAH MASOUD

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This study aims to investigate unconventional techniques for cutting a natural fiber reinforced polymer composite as alternative approaches to traditional cutting methods. Due to the cutting forces associated the conventional cutting methods and the heterogeneous nature of natural fiber composites, number of defects appear with utilizing the traditional cutting techniques, such as, poor surface quality, material damage, delamination, fiber fraying and dimensional instability. Overcoming these defects is the primary motivation for conducting this study. Taking all these aspects into account, the study formulates an investigation of laser (LBM) and abrasive water jet (AWJ) machining techniques utilized to cut sugar palm fiber reinforced unsaturated polyester (SPF- UPE). The goal is to optimize the input parameters that control the quality of the output parameters and to assess the suitability of both cutting technologies for the composite material under study. In laser beam cutting technique, the laser power, traverse nozzle speed, and assist gas pressure were selected as the input variable parameters, meanwhile the operating water pressure, traverse nozzle speed, and stand-off-distance (SOD) were chosen as input variable parameters in abrasive water jet cutting technique. Dimensional stability, surface quality, and kerf taper angle were the optimized output responses in both cutting techniques, as well as heat affected zone (HAZ) in laser beam cutting process. Taguchi's approach was used to estimate the optimum levels of the input parameters and their significance. Analysis of variation (ANOVA) was utilized to determine the contribution of every single input parameter. What is new in this study is the testing of a broad range of the input parameters values on three different material thicknesses, unlike most of the previous studies in the field that tested limited values of the input parameters with one material thickness. Both of cutting process have been made successfully and good cutting quality can be achieved. The best cutting quality in laser beam cutting process was recorded with applying laser power ranging from 200 to 400W, and traverse speed ranging from 150 to 250 mm/min for 2 mm plate thickness. The optimum parameter range was between 1000 to 1600W laser power with traverse speed ranging from 5600 to 6000 mm/min for 4 mm plate thickness, while the optimum range of input parameters in the case 6 mm thickness ranged from 2000 to 2600W laser power

and 7600 to 8000 mm/min traverse speed. In the abrasive water jet cutting process, the best results were recorded at water pressure ranging from 300 to 340 bar in all cases of material thickness with corresponding traverse nozzle speeds ranging from 2400 to 2800 mm/min for 2 mm plate thickness, 1800 to 2200 mm/min for 4 mm plate thickness, and 1200 to 1600 mm/min for 6 mm plate thickness. The experimental results of the study provide practical data for the cutting of SPF-UPE composites with AWJ and CO_2 laser machining technologies.

Abstrak tesis yang dikemukan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

PENGOPTIMUMAN PARAMETER PEMOTONGAN KOMPOSIT POLIESTER TAK TEPU YANG DITUJUKAN DENGAN SERAT PALMA GULA DENGAN MENGGUNAKAN TEKNOLOGI PEMOTONGAN LASER DAN JET AIR ABRASIF

Oleh

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Kajian ini bertujuan untuk menyiasat teknik-teknik tidak lazim untuk memotong komposit polimer diperkuat serat semula jadi sebagai pendekatan alternatif kepada kaedah pemotongan tradisional. Kerana kekuatan pemotongan yang berkaitan dengan kaedah pemotongan konvensional dan sifat heterogen komposit serat semula jadi, terdapat beberapa kecacatan yang timbul apabila menggunakan teknik pemotongan tradisional, seperti kualiti permukaan yang buruk, kerosakan bahan, pemisahan lapisan, kusut serat dan ketidakstabilan dimensi. Mengatasi kecacatan-kecacatan ini adalah motivasi utama untuk menjalankan kajian ini. Dengan mengambil kira semua aspek ini, kajian merumuskan penyelidikan teknik laser (LBM) dan jet air abrasif (AWJ) yang digunakan untuk memotong komposit poliester tidak tepu diperkuat serat kelapa sawit (SPF-UPE). Tujuannya adalah untuk mengoptimumkan parameter masukan yang mengawal kualiti parameter keluaran dan menilai kesesuaian kedua-dua teknologi pemotongan untuk bahan komposit yang dikaji. Dalam teknik pemotongan laser, daya laser, kelajuan nozel melintang, dan tekanan gas pembantu dipilih sebagai parameter masukan pembolehubah, sementara itu dalam teknik pemotongan jet air abrasif, tekanan air operasi, kelajuan nozel melintang, dan-jarak-tolak (SOD) dipilih sebagai parameter masukan pembolehubah. Stabiliti dimensi, kualiti permukaan, dan sudut kerf mengecil telah dioptimumkan sebagai tindak balas keluaran dalam kedua-dua teknik pemotongan, serta zon terjejas haba (HAZ) dalam proses pemotongan laser. Pendekatan Taguchi digunakan untuk menganggarkan tahap optimum parameter masukan dan kepentingannya. Analisis variasi (ANOVA) digunakan untuk menentukan sumbangan setiap parameter masukan secara individu. Yang baru dalam kajian ini ialah pengujian julat luas nilai parameter masukan pada tiga ketebalan bahan yang berbeza, berbeza dengan kebanyakan kajian terdahulu dalam bidang yang menguji nilai terhad parameter masukan dengan satu ketebalan bahan sahaja. Kedua-dua proses pemotongan telah berjaya dilakukan dan kualiti pemotongan yang baik dapat dicapai. Kualiti pemotongan terbaik dalam proses pemotongan laser beam direkodkan dengan menggunakan kuasa laser dari 200 hingga 400W, dan kelajuan traverse dari 150 hingga 250 mm/min untuk

ketebalan plat 2 mm. Julat parameter optimum adalah antara 1000 hingga 1600W kuasa laser dengan kelajuan traverse dari 5600 hingga 6000 mm/min untuk ketebalan plat 4 mm, manakala julat optimum parameter input dalam kes ketebalan 6 mm adalah dari 2000 hingga 2600W kuasa laser dan kelajuan traverse dari 7600 hingga 8000 mm/min. Dalam proses pemotongan jet air abrasif, hasil terbaik dicatat pada tekanan air yang berkisar antara 300 hingga 340 bar dalam semua kasus ketebalan bahan dengan kecepatan nozzle traverse yang sesuai berkisar antara 2400 hingga 2800 mm/min untuk ketebalan plat 2 mm, 1800 hingga 2200 mm/min untuk ketebalan plat 4 mm, dan 1200 hingga 1600 mm/min untuk ketebalan plat 6 mm. Hasil eksperimen kajian memberikan data praktikal untuk pemotongan komposit SPF-UPE dengan teknologi mesin AWJ dan CO_2 laser.

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LIST OF ABBREVIATIONS

AGS	Abrasive grain size
ANOVA	Analysis of variance
AWJ	Abrasive water jet
Bw	Bottom kerf width
C-FFRP	Carbon-flax fiber reinforced polymers
CFRP	Carbon fiber reinforced polymers
CNC	Computer numerical control
CO_2	Carbon dioxide
DF	Degrees of freedom
EDM	Electro-discharge machining
FFRP	Flax (natural) fiber-reinforced polymer
FRP	Fiber reinforced polymers
FTC	Full Through cutting
HAZ	Heat affected zone
HSS	High speed steel
Kt°	Kerf taper angle
LBM	Laser beam Machining
MDF	Medium-density fiber board
MRR	Material Removal Rate
MS	Mean of squares
NaOH	Sodium hydroxide
Nd: YAG	Neodymium-doped yttrium aluminum garnet
NFRPs	Natural fiber reinforced polymers

Ra	Average surface roughness
S/N	Signal-to-Noise ratio
Seq SS	Sum of squares
SOD	Stand-0ff-distance
SPF	Sugar palm fibers
SPF-UPE	Sugar palm fibers reinforced unsaturated polyester
SR	Surface roughness
SS	Sum of squares
T	Material Removal Rate
t	Material thickness
Ts	Traverse speed
Tw	Top kerf width
UPE	Unsaturated polyester
USD	Ultrasonic drilling
V_f	Fiber volume fraction
V_m	Matrix volume fraction
WA	Processed composite weight after cutting process
WB	Processed composite weight before cutting process
W_f	Fiber weight fraction
W_m	Matrix weight fraction
Wp	Water pressure
Wt%	Fiber loading by weight
ρ_c	Density of composite
ρ_f	Density of fiber
ρ_m	Density of matrix

CHAPTER 1

INTRODUCTION

1.1 Background

In light of the relentless pursuit to develop renewable, environmentally friendly sources for the production of various engineering materials, and the requirements imposed by the environmental, economic and health needs, the natural based composites or natural fiber reinforced polymers (NFRPs) were one of the most prominent solutions that employed clean environmental resources were wasted for long periods of time previously (Singh et al., 2023)(Alaaeddin et al., 2019)(Al-Oqla & Sapuan, 2014)(Ammar et al., 2019). Sugar palm fiber(SPF) reinforced polymers is one of the most promising materials to be used in various engineering applications because of its distinct physical, chemical and thermal properties based on the studies conducted on these material recently.(Ishak et al., 2013)(Sahari et al., 2011a)(Sapuan et al., 2012). Sugar palm fiber is becoming increasingly popular in the field of engineering. A novel material, which combines sugar palm fiber with glass-reinforced unsaturated polyester, was utilized to construct a small boat. This hybrid boat exhibited significantly improved mechanical properties, including a tensile modulus of 1840.6 MPa and impact strength of 2.471 kJ/m^2. Additionally, the substitution of sugar palm fiber for glass fiber led to a 50% reduction in weight, while maintaining or even enhancing the mechanical properties (Huzaifah et al., 2017). The use of sugar palm fiber (Ijuk) as reinforcement for thermoset materials has also been explored in the production of helmets. The resulting helmets have passed the Malaysian standard (MS) test administered by SIRIM QAS INT., Sdn. Bhd. In a related development, sugar palm fiber has been utilized as a soundproofing material for lining zinc roofing sheets. The same composite could be used potentially for sound proofing engine covers. (Mukhtar et al., 2016). As research on sugar palm fiber and its composites continues, additional potential applications for this composite will be discovered and implemented in a wide range of fields such as, aircraft, automobiles, marine applications, construction, packaging, electronic industries applications, sporting equipment, and so forth. Although the NFRPs composites are manufactured in near-net shape, they are still need some final cutting processes to reach the final shape perfectly suited to the application such as drilling, cutting and trimming processes.(Adapa & Jagadish, 2023)(Ismail et al., 2016)(Yahya et al., 2019)(Lotfi et al., 2019)(Rajmohan et al., 2018). Composites do not behave like conventional materials under traditional cutting processes due to the different properties of composites such as heterogeneous structure which causes some defects on the product, requiring a thorough study of the cutting properties of composites to avoid these defects or reduce their impact. (Baysal et al., 2023)(Ismail et al., 2016)(Chegdani et al., 2015)(Jani et al., 2016a)(H. Rezghi et al., 2019). Several defects arise as a result of conventional cutting process such as fiber fraying, delamination and dimensional instability due to deformations caused by cutting forces in addition to poor surface roughness (Yahya H. Çelik et al., 2019)(Abdullah & Sapuan, 2017). Cutting processes can be classified into conventional processes that utilize solid tools, including drilling, sawing and milling, and non-traditional processes including laser beam machining (LBM), ultrasonic drilling (Lotfi et al., 2019), and abrasive water jet machining(AWJ) (Dhakal et al., 2018)(Gulia & Nargundkar, 2022). According to the literature there is no study conducted to investigate and evaluate any non-traditional

techniques utilized to cut sugar palm fiber reinforced unsaturated polyester composite (SPF-UPE). Also the previous studies that targeted natural fibers composites cut with unconventional approaches were limited in general, especially the studies conducted on laser beam cutting technology. This research represents an experimental study to determine the optimum input processing parameters in cutting sugar palm fiber SPF-UPE composite with laser beam (LBM) and abrasive water jet (AWJ) machining techniques as alternative unconventional cutting processes in order to avoid defects resulting from the cutting forces associated with the cutting processes by traditional methods.

1.2 Problem statement

It is known that the cutting processes are required in order to use composites in many engineering applications, however the traditional cutting processes produced serious defects due to the high sensitivity of the composites to the cutting force associated with the traditional cutting processes (Ismail et al., 2016)(Chegdani et al., 2015). These defects are total or local deviations in the dimensions and structure of the material such as deformations or occurrence and propagation of cracks that lead to breaking or smashing of the part to be cut or punctured. The fraying and delamination damages at the cutting zone is one of the most negative results of the concentration of cutting force at the cutting zone, which represents a local failure in the structure of the composite. Also the poor surface quality at cutting zone is the one of the common defects emerged due to the heterogeneous nature of the composites and the companion cutting forces. Thus, the problem can be expressed as the appearance of serious defects on the product as a result of using traditional cutting methods due to the accompanying cutting forces and the heterogeneous nature of the composites in addition to the relatively high fixture force required to fix the specimens in the traditional cutting techniques.

Overcoming these disadvantages has prompted the researchers to consider the use of other non-traditional methods for different cutting processes of composites. Abrasive water jet (AWJ) and Laser beam (LBM) cutting technologies are one of the most unconventional methods recently used in cutting composites which have achieved good results in cutting some types of natural and synthetic fibers reinforced polymers (Lotfi et al., 2019) (Abdullah & Sapuan, 2017). Both processes have a number of important input process parameters through which the quality of the product is controlled. The controlling input parameters have to be optimized to find their best levels that give the optimum desired output responses. Although the AWJ and LBM cutting processes are relatively expensive in terms of equipment, they remain a promising solution to avoid the defects resulting from the use of traditional methods, especially the cutting process are carried out in the absence of wear of the cutting tools and high installation requirements.

To the best of our knowledge, no comprehensive study has been carried out to determine the optimum input processing parameters for cutting sugar palm fiber reinforced unsaturated polyester using abrasive water jet(AWJ) and laser beam cutting technologies (LBM), especially that, the related previous researches conducted on some types of natural fiber composites –sugar palm fiber composites is not one of them- were very

limited in general especially by laser beam cutting process, also the most of previous studies have covered one material thickness which was small in general (less than 2 mm) with low and limited ranges of input parameters values which makes their results limited in terms of generalization and application, so the questions of study can be summarized as, what are the optimal input parameters of AWJ and LBM cutting processes that produce the optimum desired parameters?, and, which of these processes is best for cutting sugar palm fiber reinforced unsaturated polyester?.

The main target of this study is to answer these questions by applying broad ranges of input parameters values on three various material thicknesses of SPF-UPE. What is new in this study is the testing of a broad range of the input parameters values on three different plate thicknesses of SPF-USP, unlike most of the previous studies in the field that examined limited values of the input parameters with one plate thickness.

1.3 Research Objectives

The overall aim of study is to investigate AWJ and LBM cutting techniques used to cut sugar palm fiber reinforced unsaturated polyester composite as alternative approaches to traditional cutting methods. The specific objectives of this research are:

1. To evaluate the cutting quality and dimensional stability of sugar palm fiber reinforced unsaturated polyester composite under cutting conditions of Abrasive water jet and Laser beam cutting technologies

2. To determine the optimum surface quality of the sugar palm fiber reinforced unsaturated polyester composite cut with Abrasive water jet and Laser beam cutting techniques by optimizing the surface roughness response.

3. To determine the optimum input parameters that produce the best kerf taper angle at the cutting zone in both cutting process.

4. To investigate the thermal effects at cutting zone (heat affected zone HAZ) in Laser beam cutting technology and find the best input parameters that produce minimum effect of accompanying heat generated by laser beam.

1.4 Significance of study

The study opens a new horizon for employing modern cutting techniques in cutting NFRPs, and it is expected to provide adequate data about input processing parameters of cutting sugar palm fiber reinforced unsaturated polyester by non-traditional methods. Also the study is expected to provide good solutions to avoid the defects that produced by cutting forces associated with conventional cutting processes methods. The study also provides a comparison between Abrasive water jet and Laser beam cutting technologies to provide data that help production engineers to choose the appropriate method for cutting sugar palm reinforced unsaturated polyester and other similar materials. The

study represents a good start point to evaluate the similar composites under same cutting conditions and study results may be generalized efficiently to use for cutting other natural fiber composites cut with same techniques. The study contributes to enriching the information aspect that helps in expanding the use of sugar palm tree, which adds another value to the tree other than sugar production.

1.5 Scope of study

In this study, the fiber raw extracted from the sugar palm tree were purified and various unwanted impurities were removed, and the fibers were cleaned well with pure water and then dried by hot air. The screened and cleaned fibers were treated chemically with sodium hydroxide solution. The treated fibers were washed with pure water, dried, and cut manually in the required lengths. The molds for specimens forming were prepared to form the composite with the required dimensions. The unsaturated polyester resin was mixed with the catalyst as per the recommendations of the resin manufacturer. The required quantities of the specimens were formed in various thicknesses by hand-lay-up technique.

Laser beam and abrasive waterjet cutting processes were made under different conditions of the significant input parameter in terms of the parameter values and material thicknesses.

An initial evaluation was conducted to determine the range of parameters that gave best cutting quality. The ranges of input parameter levels that showed material damages, incomplete cuts, or low productivity, were excluded.

The output parameters were measured and the results were analyzed and optimized by Taguchi's method to determine the best values of the input parameters and their importance in terms of the effect on the output parameters. The contributions of every single input parameter to the effect on the output parameters was determined by ANOVA method. The optimum input parameters that gave the best responses of the targeted output parameters were defined for each material thickness.

1.6 Structure of thesis

The structure of thesis is made according thesis format of Universiti Putra Malaysia that is based on the study publications. Every single research chapter represents a separate study which has its own: ‘Introduction’, ‘Materials and method’, ‘Results and discussion’, and ‘Conclusions’. The structure of thesis is explained as follow.

Chapter 1

The problem that motivated this research and the research objectives were clearly defined in this chapter in addition to the scope of study and its significance and contributions.

Chapter 2

This chapter introduces an inclusive literature review on the field related to the topic of the thesis.

Chapter 3

This chapter describes the methodology used in this research for the material forming, experiments setup, measurements and equipment, and optimization methods.

Chapter 4

This chapter presents the first research article entitled "**Experimental Investigation on Dimensional Stability and Cutting Quality in Cutting Process of Sugar Palm Fiber Reinforced Unsaturated Polyester Composites with Laser beam and Abrasive water jet cutting technologies**". In this article, the influence of input parameters values on the overall cutting quality and dimensional stability of the specimens was investigated for both cutting process techniques.

Chapter 5

This chapter presents the second article entitled "**Experimental Analysis of Surface Roughness in the Cutting Process of Sugar Palm Fiber Reinforced Unsaturated Polyester Composites with Laser Beam and Abrasive Water Jet Cutting Technologies**". In this article, the input parameters effect on the surface roughness response was investigated and optimized for both cutting process techniques.

Chapter 6

This chapter presents the third research entitled "**Experimental Analysis of Kerf Taper Angle in Cutting Process of Sugar Palm Fiber Reinforced Unsaturated Polyester Composites with Laser beam and Abrasive water jet cutting technologies**". In this article, the input parameters effect on the cutting kerf taper angle was investigated and optimized for both cutting process techniques.

Chapter 7

This chapter presents the fourth research entitled "**Experimental Analysis of Heat-Affected Zone (HAZ) in Laser Cutting of Sugar Palm Fiber Reinforced Unsaturated Polyester Composites**". In this article, the input parameters effect on the heat affected zone (HAZ) was investigated and optimized for laser beam cutting technique.

Chapter 8

This chapter introduces the overall conclusions found from the whole research and future recommendations for further improvement of this study.

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