الجامعة الإسلامية العالمية ماليزيا
INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA
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INVESTIGATION OF MACHINING PARAMETERS ON ABRASIVE WATER JET MACHINED SURFACE OF GLASS/EPOXY COMPOSITES USING TAGUCHI METHOD

BY

MOHD AZMIR MOHD AZHARI

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Kulliyyah of Engineering
International Islamic University
Malaysia

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ABSTRACT

An experimental investigation was conducted to study the influence of abrasive water jet machining (AWJM) process parameters on the machining performance criteria namely surface roughness (R_a) and kerf taper ratio (T_R) of glass fibre reinforced epoxy composites. The approach was based on Taguchi's experimental design and Analysis of Variance (ANOVA) to optimize the AWJM process parameters for effective machining. It was found that the type of abrasive materials, hydraulic pressure, standoff distance and traverse rate were the significant control factors and the cutting orientation was the insignificant control factor in controlling the machining performance criteria in both cases. It was also confirmed that increasing the kinetic energy of water jet may produce a better quality of cuts. Based on analysis of mean (ANOM) for noise factors effect, it was found that the form of glass fibre and thickness of composite laminate gave greatest influence on R_a machining criteria and for T_R, it was found that each noise factor had relatively an equal influence on it. Mathematical models were developed using linear regression analysis to predict the R_a and T_R in terms of the cutting parameters of AWJM. The models successfully predicted the R_a and T_R of an AWJ machined glass/epoxy laminate within the limit of this study. For effective machining of glass fibre reinforced epoxy composites, verification of the improvement in the quality characteristics has been made through confirmation test with respect to the chosen initial parameter setting. The recommended optimal parametric combinations for better R_a and T_R are A2B3C1D3E1F2 and A2B3C1D3E1F3 respectively. In case of R_a, the improvements of S/N ratios with respect to the initial parameter setting were 3.031 dB, 3.638 dB, 2.635 dB and 3.743 dB respectively for sample 1, 2, 3 and 4 meanwhile, in case of T_R the improvements of S/N ratios were 12.153 dB, 3.202 dB, 10.803 dB and 21.178 dB respectively. It was confirmed that determined optimal combination of AWJM parameters satisfy the real need for machining of glass fibre reinforced epoxy composites in practice. It was proven that various analyses based on Taguchi's experimental design, quantitative modelling and experimental results as obtain through the present study were useful for analysing the influence of various process parameters for achieving suitable control over the machining quality criteria.

ملخص البحث

هذه الاطروحة تشمل البحث عن العوامل المؤثرة على تأدية مكائن القشط باستخدام الماء على خشونة السطح، ونسبة أطوال الشق لألياف الزجاج. الطريقة معتمدة على طريقة تاجوشي، وتحليل الاختلاف للوصول إلى أقصى وأحسن قيم للعوامل المنتجة للقطع الفعّالة. لقد وُجد أنّ نوعية المواد القاشطة، الضغط الهيدروليكي، والنسبة بين المسافة بين الماء المنبثق، والقطع والحاجز، ومعدل القشط كانت هي أهم العوامل المسيطرة وأما توجيه القطع فقد كان أهم العوامل المؤثرة في السيطرة على تأدية القطع في الحالتين. كما تم إثبات أن زيادة الطاقة الحركية للماء المنبثق تؤدي إلى نوعية أحسن للقطع، اعتمادا على تحليل معدل تأثير عوامل الضوضاء، فقد وجد أنه شكل ألياف الزجاج، وسماكة تركيبة الرقائق لها الأثر الكبير على خشونة السطح، ونسبة أطوال الشق. كما وجد أن عامل الضوضاء له تقريبا تأثير متساويا عليه. تم تطوير الموديل الرياضي باستعمال التحليل الارتدادي الخطي للتنبؤ بخشونة السطح، ونسبة أطوال الشق حسب عوامل مكائن القشط باستخدام الماء. والموديلات تنبأت بنجاح، بخشونة السطح، ونسبة اطوال الشق للزجاج المقطوع، ورقائق الايبوكسي ضمن حدود هذه الدراسة. وأحسن مكننة لألياف الزجاج تتقوى بتركيبة الايبوكسي. تأكيد التحسينات بنوعية المواصفات، تم تأكيدها بفحوصات حسب العوامل الأولية المختارة. أقصى تشكيلة للعوامل الموصى بها لأحسن خشونة السطح، ونسبة أطوال الشق هي أ2ب3ج1د3ي1ف2 وأ2ب3ج1د3ي1ف3 بالتتابع. في حالة خشونة السطح، التحسين بنسبة س/ن فيما يتعلق بتثبيت العوامل الاولية كانت 3.031 ديسبل، 3.638 ديسبل، 2.635 ديسبل و3.743 ديسبل بالتتابع للنماذج 1، 2، 3 و4. في حالة نسبة أطوال الشق فإن التحسينات بنسبة س/ن كانت 12.153 ديسبل، 3.202 ديسبل، 10.803 ديسبل و21.178 ديسبل بالتتابع. تم التاكيد على تشكيلة العوامل القصوى التي تشبع الحاجة الفعلية لقطع ألياف الزجاج المقواة بتركيب الايبوكسي في التطبيق. تم إثبات أنه التحاليل المختلفة اعتمدت على تجارب تصميم تاجوشي، النموذج الكمي والنتائج العملية التي تم الحصول عليها في هذه الدراسة كانت مفيدة لتحليل عوامل العمليات المختلفة للوصول إلى السيطرة المناسبة على نوعية القطع.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science (Manufacturing Engineering)

…………………………………………
Ahsan Ali Khan
Supervisor

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science (Manufacturing Engineering)

…………………………………………...
Mustafizul Karim
Internal Examiner

…………………………………………...
Che Hassan Che Haron
External Examiner

This dissertation was submitted to the Department of Manufacturing and Materials Engineering and is accepted as a partial fulfilment of the requirements for the degree of Master of Science (Manufacturing Engineering)

…………………………………………
Shahjahan Mridha
Head, Department of Manufacturing and Materials Engineering

This dissertation was submitted to the Kulliyyah of Engineering and is accepted as a partial fulfilment of the requirements for the degree of Master of Science (Manufacturing Engineering)

…………………………………………
Ahmad Faris Ismail
Dean, Kulliyyah of Engineering

DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Mohd Azmir Mohd Azhari

Signature ……………………….   Date ………………..……

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DECLARATION OF COPYRIGHT AND AFFIRMATION OF FAIR USE OF UNPUBLISHED RESEARCH

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Affirmed by Mohd Azmir Mohd Azhari.

………………………….. ………………….
Signature Date

I dedicate this work to my beloved parents, wife and 'Afeef

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In the name of Allah, the most merciful and the most compassionate.

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LIST OF ABBREVIATIONS

A.W.J.M	Abrasive water jet machining
G.F.R.P	Glass fibre-reinforced polymer
D.O.E	Design of experiment
ANOVA	Analysis of variance
M.M.C	Metal matrix composite
C.M.C	Ceramic matrix composite
C.B.N	Cubic boron nitride
SiC	Silicon carbide
F.R.P	Fibre-reinforced plastic
A.W.J	Abrasive water jet
E.D.M	Electrical discharge machining
H.S.S	High speed steel
TiN	Titanium nitride
TiC	Titanium carbide
et al.	(*et alia*): and others
MPa	Mega Pascal
C.N.C	Computer numerical control
S.P.S.S	Statistical package for social science
M.S.D	Mean-squared deviation
D.O.F	Degree of freedom
S.S	Sum of squares
V	Variance
ANOM	Analysis of means
V.I.F	Variance inflation factor
N.P.P	Normal probability plot
W.C	Tungsten carbide

LIST OF SYMBOLS

ρ	Specific density (g/cm^3)
σ	Tensile strength (GPa)
E	Modulus of elasticity (GPa)
υ	Poisson's ratio
V_f	Fibre volume fraction (%)
ρ_f	Density of fibre
ρ_m	Density of matrix
W_f	Weight of fibre
W_m	Weight of matrix
W_c	Weight of composite
W_b	Bottom kerf width
W_t	Top kerf width
R_a	Surface roughness
T_R	Kerf taper ratio
S/N	Signal to noise

CHAPTER ONE

INTRODUCTION

1.1 GENERAL BACKGROUND

Abrasive water jet machining (AWJM) process is one of the non-traditional machining processes that has been used extensively in various industry-related applications. It is applied in almost all forms of modern industries, including the automotive industry, aerospace industry, construction engineering, cleaning processes, mining and demolition, industrial machining and maintenance. The basic principles of abrasive water jet machining (AWJM) were reviewed in detail by Momber and Kovacevic (1998).

In general, the abrasive particles are mixed with a stream of high-velocity water to form a slurry cutting jet to cut various materials from typical metals, ceramics, glass, rock and stone to high strength advanced composites and superalloys. Its capability to cut different types of materials of different thickness is much depended on the choice of various processing parameters such as hydraulic, mixing, abrasive and machining parameters. Water serves as an accelerating medium and abrasive particles serve as removing materials. Primarily, water is compressed to an ultrahigh pressure up to about 400 MPa and discharged from a small orifice of 0.01-0.02 mm in diameter made from hard materials such as sapphire. The system produces a high velocity water stream up to 915m/s, together with abrasive particles causing damage to materials by shearing, cracking, erosion, cavitation, delamination and plastic deformation (Arola and Ramulu, 1993).

The use of composite materials has become prominent in today's modern technology applications. There is a need to develop new improved materials in terms of mechanical properties to substitute conventional materials where their uses become limited. It is true especially in aerospace, marine and transportation industries that require structural materials having better mechanical properties such as low density, high strength and stiffness, abrasion and impact and corrosion resistance. This can be realized by combining two or more different materials which can produce a better combination of properties from both constituent phases (Callister, 2003:5; Komanduri, Zhang and Vissa, 1991). Strong (1989: 2) gives more specific definitions of composite materials as a combination of a reinforcement material in a matrix or binder material. The reinforcement materials are generally, fibres, particles and whiskers meanwhile the matrices are polymers, ceramics and metals (Strong, 1989: 2). Callister (2003: 547) classify composites into three types: particle-reinforced, fibre-reinforced and structural composites.

Fibreglass or better known as glass fibre-reinforced polymer (GFRP) is simply a composite consisting of glass fibres as reinforcement materials and a polymer as the matrix; this type of composite is produced in large quantities (Callister, 2003: 547; Strong, 1989:49). Fibreglass is widely used as a reinforcement of composite materials due to its special characteristics like high weight to strength ratio, ease of availability and fabrication, corrosive resistance, good design flexibility, good electrical insulation, high fatigue endurance limit and cost effectiveness in certain manufacturing methods (Callister, 2003:547; Strong, 1989:5).

Out of several types of glass fibres manufactured, only four are used extensively in composites namely E-glass, S-glass, C-glass and quartz (Strong, 1989:49). The classifications of glass fibres are based on its compositions and properties. E-glass fibres are most commonly used as the reinforcement since it is less expensive and has a moderate strength and high electrical resistivity, while S-glass possesses 40% higher in strength than E-glass. Therefore, applications of S-glass is mostly confined in advanced composites where strength is a premium. C-glass is used in corrosive environments because of its chemical stability and quartz is used in electrical applications where a low dielectric material is required (Strong, 1989: 49-50). Figure 1.1 shows some basic forms of fibreglass which are commercially available in the market.

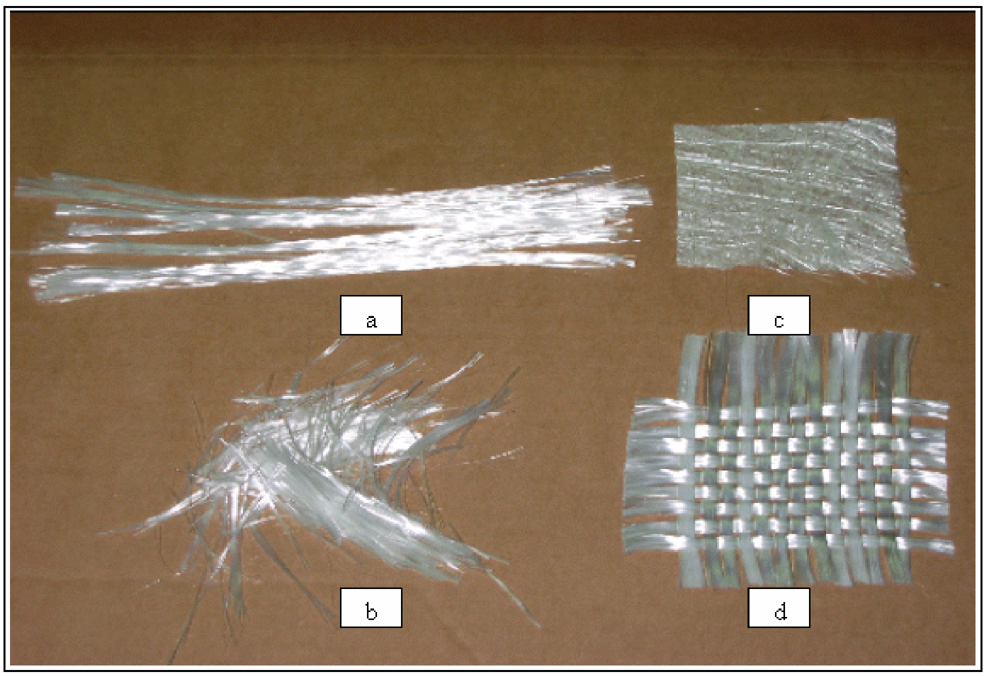

Figure 1.1

Forms of fibreglass (a) continuous strand roving (b) chopped strand (c) chopped strand mat (d) woven roving (Picture courtesy of Ahmed Nazrin, (2005))

The matrix in composite acts in two major roles as transferring loads to the reinforcement and protecting the reinforcement from adverse environmental effects (Strong, 1989: 15). The most common matrix materials used for advanced composites and for a variety of demanding applications is thermosetting epoxy. It is used widely due to its excellent adhesion, strength, low shrinkage, corrosion protection, processing versatility and electrical properties. However, epoxy may not perform well in high temperature applications like polyimide and may be more expensive as well than polyester, despite its excellent properties.

1.2 WATER JET MACHINING PROCESS

The use of AWJM which was commercialized since 1983 becomes popular in a large number of applications in various sectors mainly due to its ability to perform better machining processes compared to conventional machining processes (Hashish, 1991). This technology is less sensitive to material properties as it does not cause chatter, has no thermal effects, impose minimal stresses on the workpiece, has high machining versatility and high flexibility. But, the process has certain drawbacks especially in making loud noise and creating a messy working environment (Choi and Choi, 1997; Wang and Wong, 1999). Therefore, it is very important to work with AWJM process in a safe and conducive working environment since it involves a lot of potential safety and hazardous issues.

The process of material removal in AWJ cutting technology is based on the use of pressurized water which produces a high velocity of water jet with addition of abrasive particles to form continuous slurry to cut the target material by means of erosion. The abrasive particles act as the erosive medium meanwhile the high pressure of water acts as the accelerator, providing a diverse group of micro-machining mechanisms assisting in material removal process (Ramulu and Arola, 1994). The erosion process consists of two different mechanisms depending upon the types of eroded materials whether it is ductile or brittle material (Chen and Siores, 2001). Chen and Siores defined ductile erosion as a cutting process in which the abrasive particles progressively gouge the target material to remove the materials while in brittle erosion it is a cracking process in which material is removed by the propagation of cracks around the abrasive particles.

1.3 TAGUCHI METHOD VERSUS CLASSICAL DOE

Design of experiments (DOE) was first introduced by Sir R.A. Fisher in England in the early 1920s intended to study the effects of multiple variables simultaneously and most economically using a statistical technique (Roy, 2001: 9). The process of DOE is carried out for quality improvement purposes. Using DOE, all combinations of the factors included in experimental study are able to be laid out for investigation purposes. If the number of combinations possible is too large, then a fraction of the total possibilities is conducted such that all factors will be evenly present. Fisher devised the first method that made it possible to analyze the effect of more than one factor at a time (Roy, 2001: 3). The combinations are created using a matrix, which allows each factor an equal number of test conditions. Statistical calculations such as average and analysis of variance (ANOVA) are used to analyze the results of such experiments. By studying the effects of individual factors on the results, the best factor combination can be determined. When applied to product or process design, the method helps to seek out the best design among the many alternatives.

Dr. Genichi Taguchi, a Japanese scientist proposed a new experimental strategy. This strategy utilizes a modified and standardized form of DOE by creating a special set of tables of numbers or orthogonal arrays, each of which is used for a number of experimental situations. The results are used to evaluate the signal-to-noise ratio for analysis of repeated results to assure a design that is robust to the influence of uncontrollable factors (Roy, 2001: 10). DOE using the Taguchi approach is an entirely new process of strategies for improving quality. The method may involve on how to design experiments, how to conduct them, and how to analyze the results.

The methods of DOE (Taguchi or otherwise) can be used to solve scientific problems which involve determining a proper combination of factors, ingredients, parameters and variables rather than innovations or a single identifiable cause. In general, it is applicable to any situation that depends on many influencing factors. It is a method that scientifically gives the best option when facing with many possibilities. It is possible to investigate one factor at a time to determine the effect of the factor but it is not necessarily true since factors are interacting with each other in real-life application. Real behaviour of the factors can be studied when the influences of all factors have an equal opportunity to be present. Therefore, it is recommended to apply the DOE technique to capture such effects. The number of experiments necessary depends on the number of factors and their levels. Generally, the larger the number of factors, the greater the reduction is from the total possibilities in a full factorial experiment.

There are two different factors affecting the desired quality characteristics. The first type of factor is the control factor which has been discussed at large previously. It is a factor that can be controlled easily especially involving the machining parameters. The second type of factor is noise factor that can influence the performance of a system and are beyond our control during the intended use of the product or machine (Fowlkes and Creveling, 1995: 167). Generally, these factors are controlled by customers. It is chosen by the customer for input to the system for example in this study it can be the choice of different forms of fibreglass used as reinforcement materials namely chopped and woven fibres.

1.4 PROBLEM STATEMENT

For success in machining advanced composites, a wide range of cutting tools are needed since the geometry and material of a tool depend on both the characteristics of the matrix and the reinforcement materials. The orientation of the reinforcement fibres and the structural characteristics of composites must not be altered during machining. Most of the available tools are having difficulties in maintaining this design criterion especially involved in homogeneous composites such as metal matrix composite (MMC) and ceramic matrix composite (CMC) (Hashih, 1991, 1995). Generally, traditional machining techniques are applied to machining of composites in view of its availability and experience despite the fact that response of composites to machining is entirely different to metal machining and even in some applications with a tool harder than the work material may not be an economical proposition at all (Komanduri et al. 1991). Excessive tool wear is always a major problem in traditional machining process which results in material degradation. Most of the cutting tools used are made from hard materials such as cemented carbides, ceramics, cubic boron nitride (CBN) and diamond since the reinforcement fibres are hard but in some cases, certain machining operations are not possible at all to perform on composite materials like SiC whisker reinforced alumina with single point cutting tool even made of diamond (Komanduri et al., 1991).

Although composites are often moulded to a near-net shape, but in some cases there is a need to do net shape trimming of post-mould fabrication of fibre-reinforced plastics (FRP). Traditional machining processes for net shape trimming have shown limited potential for composite materials and may cause various forms of material damage including both inter- and intra-laminar delamination, fibre pullout and rough surface finish due to high tool wear rates. Even it is also difficult to make holes and slots without damaging the fibres around them (Arola and Ramulu, 1993). Consequently, conventional machining process may often require a secondary rework or finish machining as geometric tolerances are not achievable.

Due to the nature of fibre materials which is inhomogeneous in structure and lack of plastic elongation due to its brittleness, fine and powdery chips of fibre and resin particles together with a high proportion of dust are released into the air during the machining of composite materials (König and Rummenhöller, 1993; Komanduri et al., 1991; Hocheng, Tsai, Shiue and Wang, 1997). These fibrous materials by-products generated due to conventional machining of composite materials are hazardous to health and may cause cancer. Such kind of materials should not be disposed off to the environment (Komanduri et al., 1991).

The AWJM process provides a single tool that is suitable for machining a wide range of composite materials. It is a non-contact, inertia-less and faster cutting process that offers some advantages like narrow kerf width, negligible heat affected zone, reduced waste materials and flexibility to machining process in different ways (Hashish, 1991). In the AWJM process, the possibilities of environmental contamination due to fibrous materials are significantly reduced or eliminated since water jet washes away the eroded material from the surface of the workpiece (König and Rummenhöller, 1993).

There are many associated parameters and factors of AWJM process that influence the surface quality of the AWJ machined surface. For example, in this study only six of these factors are considered for analysis where one factor was varied to two-levels while other five factors were varied to three-levels. By using a conventional experimental methodology, it would take 486 distinct test conditions to study all of the factors and their levels, in order to determine the main influencing