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ABRASIVE WATER JET MACHINING OF COMPOSITE BALLISTIC MATERIAL (KEVLAR)

BY

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ABSTRACT

Recently, there has been a development of modern ballistic armor due to the creation of high performance composite materials based on aramid fibers with better weight reduction, higher strength and toughness. The use of metal for many critical applications has dramatically decreased since the new composite materials such as aramids provide excellent protection against handgun level threats. However, aramid fibers (Kevlars) are very difficult to machine by conventional machining techniques which cause various forms of material damage such as delamination and fiber pullout that normally occur during the machining of composite materials. The processes also result to high tool wear rates and poor surface roughness which ultimately may cause costly secondary rework as well as part rejection. As the use of these composite ballistic materials is anticipated to be increasing in large volume, the processing costs will be an important factor in order to provide cost-effective components and to gain competitive advantages over other materials. In this thesis, abrasive water jet (AWJ) machining of a representative ballistic material namely Kevlar-reinforced phenolic, an aramid fibers and a product of Du Pont was used to conduct the machining experiments in order to determine the viability of the machining process for manufacturing protective components with the above materials. Design of experiments (DOE) and analysis of variance (ANOVA) were used to measure systematically the various parametric combinations of pressure, standoff distance, traverse rate and abrasive flow rate on the kerf taper and the changes of surface roughness as a function of cutting depth for the Kevlar composite specimens. Stylus profilometry was used to measure the surface roughness and a visual inspection including scanning electron microscopy (SEM) was conducted. It was found that a smoother surface is obtained at the mid region along the depth of the specimens compared to that at the region of jet entry and jet exit. It was also observed that a higher jet pressure and a low traverse rate produces a smoother surface. Width of the kerf both at the jet entry and the jet exit was found to have a decreasing tendency with increase in traverse rate. Mathematical models were formulated to predict the surface roughness and kerf taper in terms of the selected cutting parameters mentioned earlier for the Kevlar composite to the cutting depths of 9.2mm. The cut surface of this material using a band saw machine was compared with that of the water jet in terms of surface roughness and damages incurred.

ملخص البحث

هنالك تطورات حدثت مؤخراً في صناعة دروع المقذوفات الحديثة، ويعزى ذلك إلى إنتاج المواد المركبة ذات الأداء العالي والتي تعتمد على ألياف معدن الأراميد الذي يمتاز بالوزن الخفيف والقوة العالية والقدرة على تحمل الصدمات. ونتيجة لهذا فلقد تضائل استخدام المعادن في عدة تطبيقات حيث أن المواد المركبة الحديثة (مثل معدن الأراميد) تُوفر حمايةً ممتازة مقابل التهديد الذي يسببه المسدسات اليدوية وما في مستواها. ورغم هذه الأهمية إلا أن ألياف الأراميد (أو ما يعرف بالكيفلار) ليس من السهل تشغيلها بواسطة أساليب التشغيل الآلي التي تُسبب أنواعاً عديدة من الضرر للمواد مثل عمليات تفكك الطبقات من بعضها البعض وانسحاب الألياف من المادة الأصلية وهذه العمليات عادةً ما تَحدثُ أثناء عملية التشغيل الآلي للمواد المركبة. هذا كله يؤدي إلى معدلات تآكل عالية لأدوات التغشيل بالإضافة إلى خشونة ورداءة السطح للمواد المركبة والتي تتطلب في النهاية عمليات إعادة تصنيع مكلفة بالإضافة إلى رفض الأجزاء التي تم تصنيعها. ومع توقع زيادة حجم استعمال هذه المواد المركبة في مجال المقذوفات فإن تكاليف التصنيع تكون عاملاً مهماً لإنتاج مواد أقل تكلفة وأكثر كفاءة وذات مميزات تنافسية أفضل مقارنةً بالمواد الأخرى. استخدمت هذه الدراسة آلة التشغيل المعتمدة على نفاث مائي لكشط الأسطح حيث تم أخذ عينات من مواد المقذوفات وبالتحديد مواد الفينوليك المدعومة بالكيفلار وألياف الأراميد وأخيرا مواد مركبة من إنتاج شركة ديبون لإجراء تجارب التشغيل لتحديد فاعلية عملية التشغيل الآلي باستخدام الآلة المذكورة لتصنيع دروع من المواد السابق ذكرها. وقد تم تصميم التجارب وتحليل الفروقات الإحصائية لقياس تأثير المتغيرات المختلفة مثل الضغط، والمسافة بين الآلة وسطح التشغيل، ومعدل الحركة الأفقية للآلة، بالإضافة إلى معدل سريان الكشط والتغيرات في خشونة السطح كدالة في عمق القطع في عينات مواد الكيفلار المركبة. استخدم الباحث المقياس الإبري لقياس خشونة السطح بالإضافة إلى الفحص البصري وميكروسكوب المسح بالإلكترونات. كما تم وضع نماذج رياضية للتنبؤ بمدى خشونة السطح وقطع المنشار مخروطي الطرف فيما يخص مقاييس القطع المذكورة سابقاً والخاصة بمادة كيفلار المركبة بعمق 9.2 من المليمتر. تم أيضا مقارنة السطح المقتَطَع من هذه المادة باستخدام كلا من منشار آلي وآلة التشغيل المستخدمة في هذه الدراسة وذلك فيما يتعلق بخشونة السطح والضرر الناتج للمادة المركبة.

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 thesis for the degree of Master of Science in Manufacturing Engineering.

……………………………………...
Assoc. Prof. Dr. 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 thesis for the degree of Master of Science in Manufacturing Engineering.

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Prof. Dr. Ahmad Faris Ismail
Internal Examiner

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 thesis for the degree of Master of Science in Manufacturing Engineering.

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Prof. Dr. Ahmad Faris Ismail
Dean, Kulliyyah of Engineering

DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by footnotes giving explicit references and a bibliography is appended.

Name: Rahmah Bte Abdullah

Signature:.. Date: . ……………………….

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

To Zulkurnain

and my children, Fatin, Amir and Afiq.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Recently, there has been considerable interest in the use of water jet cutting technology. Water jets are versatile, non-traditional machining tools that are currently used in many different industrial operations especially in the cleaning processes, mining and demolition, industrial machining and impulse fragmenting (Fabien et al. 2002). In industrial cutting applications, the high pressure jets mixed with abrasives, are used for precision cutting or trimming both linear and complicated contours over a range of surfaces with little distortion of the final work surface. This particular cutting tool not only can cut simple but also complex shapes of numerous materials. For example, by using pure water, it is possible to cut textiles, paper, thin plastics, wood and even food products. Whereas, thicker and harder materials such as glass, steel, ceramics, stone, composites, etc can easily be cut with the addition of an abrasive provided in the water jet system. In the principle of water jet machining, water is compressed to ultrahigh pressures of 380-400 Mpa (60,000 psi) and then released through a small orifice made of a hard material such as sapphire or diamond of 0.01-0.02 mm in diameter. The stream attains an estimated speed of up to 2,700 ft/s (915 m/s) or 2.5 times the speed of sound with sufficient kinetic energy to cut or slice through most non-metals and thin metallic materials, carrying away most of the heat generated in the process, thereby eliminating the thermal and minimizing machined surface distortion (Ramulu 1993). The high-pressure water jets were originally introduced to be used for washing away clay and rock in mining operations. Only during the late 1960s, water jet cutting technology has gained its potential use in trimming the newly developed composite materials for aerospace application. Manufacturing is always looking for ways to lower its cost and increase its throughput while maintaining quality. Thus, the new water jet (WJ) machining method has then replaced the conventional industrial saws which usually created mechanical and thermal stresses that damage the composites and render them unusable. Later, in the early 1980s, abrasive particles, serve primarily as the erosive medium, were introduced into high-pressure water jets forming the abrasive water jet (AWJ) with the capability of high removal rates for the machining of harder industrial materials including precision machining (Ramulu 1993). According to a survey in 1995, 90% of the AWJ shops use garnet, 15% olivine, 15% slag, 11% aluminium oxide and 11% silica-sand as the abrasive materials (Momber & Kovacevic 1998: 5). Abrasive water jet (AWJ) has then been applied to cut a wide range of materials including metallic materials and traditionally difficult-to-machine or cut materials such as glass, ceramics, and composites (Ramulu 1993). Besides cutting, the versatility of the abrasive water jet technology has also made possible other manufacturing processes such as milling, turning , piercing and finishing (Momber & Kovacevic 1988: 284).

1.2 Background

Indeed, water jet (WJ) and abrasive water jet (AWJ) are receiving considerable attention and have been introduced at the industrial level because of the beneficial characteristics of material removal. The high velocity jet of water transfers momentum to the abrasive particles, accelerating them to their impingement on the work piece (Ramulu 1993: Wang and Wong 1999). Specific advantages of these machining methods in relation to their ability to machine difficult-to-cut materials without thermal stresses and their omni-directional cutting capability (ability to cut in any direction) has given the most promising technique to be applied in machining composites (Ramulu and Arola 1993). By having its remarkable potential, both WJ and AWJ systems have been suggested for the machining of fiber-reinforced composites (FRP) which have made significant contributions in today's technology such as in the aerospace applications in which Graphite/Epoxy composite has been widely used (Ramulu and Arola 1994,1996: Colligan et al.1993). Composite materials offer not only high strength-to-weight ratios and stiffness-to-weight ratios but also possess increased toughness and greater reliability along with good corrosive resistance properties (Ramulu et.al 2001). Aramid fiber reinforced plastics (AFRP) or Kevlar, in particular, is no exception. The development of modern ballistic armor based on aramid fibers namely as Kevlar- reinforced phenolic is now being envisaged to be competitive and impressive in the industry of protection technology for use as ballistic armor. However, as with other composite materials, Kevlar poses a lot of problems for its manufacturing process especially in machining.

1.3 Problem Statement

1.3.1 Hazardous Dust Problem

Firstly, due to inhomogenous structure of composites and lack of plastic elongation, fine, powdery chips and fiber particles together with a high proportion of dust will be released into the air during the machining of the materials (König et al. 1985: Komanduri et al. 1991: König and Rummenhöller 1993). Thus, industrial safety regulations require that particular attention be paid to the dust generated during the machining process, since some of them is very fine and, therefore, dangerous to health (König and Rummenhöller 1993). Furthermore, some of the chemicals released due to heat and thermal damage during the machining of polymer based composites, can be harmful. Since fibrous materials such as asbestos has been established to cause cancer and other fibers are also suspected agents, the effect of airborne fibrous glass and dust originating from machining fiber reinforced plastics (FRP) have come to attention for study (Komanduri et al. 1991). Both inorganic fibers and organic compounds released during machining of polymer based composites can cause respiratory and other medical problems. Even though fibers used in composites have diameter ranges from 9-24 μm are not respirable, the split fibers during machining could be very hazardous. For instance, the measurement of size distribution of dust and fiber particles is found to be smaller than 5 μm and respirable which definitely can impair the health of the operator in present and cause machine tool damage (König and Rummenhöller 1993). However, environmental concerns such as airborne contaminants and fumes related to the cutting of fibrous materials is expected to be significantly reduced or eliminated through the use of a water jet cutting system since water jet washes away the eroded material from the surface of the work piece.

1.3.2 Machined Surface Quality and High Tool Wear Rates

Secondly, post-mold fabrication of fiber-reinforced plastics (FRP) has become a challenging task for today's manufacturing engineers in which more efficient methods of net shape trimming are required (Ramulu and Arola 1993: Wang et al.1995). Even though a majority of composite components can be produced by near-net-shape manufacturing methods, composite parts often require post-mould machining and drilling to meet dimensional tolerance, surface quality and other functional requirements (König et al. 1985: Wang et al.1995). Moreover, it is also still difficult to mould holes and slots without disturbing the fibers around them (Ramulu and Arola 1993). It is only through machining that intricate shapes and desired tolerances can be produced. However, the material behaviour of fiber reinforced composites is inhomogeneous due to the diverse fiber and matrix properties, fiber orientation, and relative volume of matrix and composites which limit the potential use of traditional methods for net shape trimming. Therefore, the machining of fiber-reinforced composite materials (FRCM) differs significantly compared to conventional metallic materials and always poses problems not frequently seen for metals due to the non-homogeneity, anisotropy and their abrasive characteristics. For instance, most fibers used in composites such as glass, carbon and aramid are hard and abrasive in the soft matrix composite such as aluminium, magnesium, epoxy and polyester resins, making them as difficult-to-machine materials that impose special demand on the geometry and abrasive resistance on tool materials (König et al. 1985). Polycrystalline diamond (PCD) tool materials have shown excellent wear resistance with superior surface finish for the machining of Graphite/Epoxy which have led to an increase in the use of PCD inserts for drilling and edge trimming operations (König and Rummenhöller 1993: Wang et al. 1995). However, damage to the material is an important quality-related characteristic for the evaluation of the composite workpiece. Delamination which is regarded as a resin or matrix dominated failure mode in the interply region is a typical damage phenomena most frequently occur during the machining of composites such as aramid, carbon epoxy or glass fiber materials. Fraying is also identified as a damage which result from fibers protruding from the machined surface. Meanwhile, other typical problems encountered include spalling, splintering, cracking and edge chipping (Ramulu et al. 2001: König and Rummenhöller 1993). The risk of damage is found to be greater during machining operations involving unidirectional laminates since there is no mechanical link between unidirectionally oriented fibers compared to the ones involving fabric reinforced (König and

Rummenhöller 1993). Furthermore, the quality of cut surface when machining fiber reinforced thermoplastics depends largely on the angle between the fiber orientation and the machining direction (König and Rummenhöller 1993: Wang et al. 1995). This produces different levels of surface quality in accordance with the orientation of the fibers in relation to the tool feed direction. Indeed, due to the high tool wear and high costs of tooling experienced with conventional machining, water jet cutting technology has been envisaged to offer an attractive alternative as non-contact material removal process in the manufacturing of composite materials.

1.4 Objectives of the Study

The objectives of this thesis are as follows:-

1. To study the influence of abrasive water jet (AWJ) cutting parameters on the surface quality and kerf taper of an abrasive water jet machined Kevlar dominated ballistic material namely, Kevlar-reinforced phenolic. Surface quality in terms of surface roughness and kerf geometry are designated as criteria for assessing the AWJ of the machined surface. Whereas, kerf width and taper are serious considerations when cutting expensive materials such as composites. Reduced kerf taper is very important to allow parts to be positioned closer together as well as to save material which ultimately can optimize material use and increase cost-effectiveness.
2. To examine the machined surface that will be conducted with the aid of an optical microscope, scanning electron microscope (SEM), and surface profilometer.
3. To compare the surface quality of the AWJ machined samples with that of traditional band saw cutting.

4. To develop empirical models for the prediction of surface roughness and kerf taper in terms of the selected cutting parameters for the material under study.

1.5 Significance of the Study

1.5.1 Hard-to-Machine Composite Ballistic Material - Kevlar

As the use of composite structures becomes ever more demanding and widespread, the use of different fibers other than fiberglass and carbon fibers is likely to increase. Today, the use of metal for many threat levels has been dramatically decreased due to the development of high performance synthetic composite materials such as the one that is based on aramid fibers. The creation of aramid fibers called 'Kevlar' has led to the big breakthrough in the development of modern ballistic armor due to its unique properties of special applications in armor which give ballistic protection (Brent Strong, http://www.cfa-hg.org/documents/Polymeric). The performance of aramid fibers Kevlar, a space-age material designed by Du Pont industries, is appealing when weight and toughness are major considerations. Kevlar is a manmade organic fiber ever developed, with its unique combination of properties allowing for high strength with low weight, high chemical resistance, and high cut resistance. The material is also flame resistant; does not melt, soften, or flow; and the fiber is unaffected by immersion in water (Brent Strong, http://www.cfa-hg.org /documents /Polymeric). Kevlar is also known to be five times stronger than steels and ten times than aluminium (http://blackarmor.com/Car_MaterialSpecs.htm). By using Kevlar in conjunction with resins like those to make fiberglass, it is possible to mold Kevlar in composite armor. This type of composite has its applications in ballistic helmets and lightweight armored vehicle as well as bank counters, safe rooms, and guard stations. Being an armor material, Kevlar protects against ballistic attacks