ANALYSIS OF MATERIAL REMOVAL RATE AND RECAST LAYER IN MICRO-EDM OF NON-CONDUCTIVE ZIRCONIA

BY

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ABSTRACT

Inconsistency in material removal rate (MRR) and minimizing recast layer are critical issues in non-conductive ceramic machined using micro-EDM. Thus, this research presents the analysis of MRR and recast layer of zirconium oxide (ZrO_2) due to micro-EDM using EDM-3 dielectric fluid and tungsten tool electrode. The investigation was performed using multi-process micro machine tools. The two main parts of this research are process development and the analysis of MRR and recast layer. For process development, assisting electrode (AE), polarity, flushing, feed rate, gap voltage, and rotational speed were the control parameters. The machined parts were observed using scanning electron microscope. The better machinability of ZrO_2 was found to be with copper adhesive as AE, positive polarity of workpiece, feed rate 3 µm/s, and workpiece submerged in dielectric fluid with one way circulation. The best conditions in process development were used as the fixed parameters. Rotational speed and gap voltage were the control parameters for the analysis of MRR and recast layer. The results of MRR were obtained by measuring the mass of material removed over machining time. The recast layer hardness was measured using micro-Vickers hardness tester. The MRR and hardness data were analyzed and empirical models were developed using design expert software. The optimum parameters for maximum MRR found to be 375 rpm rotational speed and 80 V gap voltage. The optimum value for minimum recast layer hardness was 874.8 Hv with rotational speed of 378 rpm and gap voltage of 110 V.

ملخص البحث

يعد التفاوت في معدّل إزالة المواد (التشغيل) وكذلك تقليل الطبقة المعاد صياغتها من القضايا الحرجة في عملية تشغيل مادة السيراميك غير الموصلة كهربائياً عن طريق إستخدام التشغيل بالتفريغ الكهربائي الدقيق (المايكروي). بالتالي فإنّ هذا البحث يقدم تحليل لمعدّل إزالة المواد وكذلك إعادة صياغة طبقة أوكسيد الزركونيوم (ZrO_2) بواسطة التفريغ الكهربائي الدقيق (المايكروي) عن طريق ماكنة التفريغ الكهربائي ثلاثية الأبعاد ذات السوائل العازلة للكهرباء وأداة قطب التنغستن. تم إجراء هذه العملية باستخدام هذه الماكنة متعدّدة العمليات المايكروية. القسمان الرئيسيّان في هذا العمل هما عملية التطوير وكذلك تحليل معدّل إزالة المواد في التشغيل وعملية إعادة صياغة الطبقة. بالنسبة لعميلة التطوير فإنّ إسناد القطب، الإستقطاب، تدفّق السائل العازل، معدّل التغذية، قيمة فرق الجهد وسرعة الدوران هي معلّمات أو معايير السيطرة. الأجزاء المشغّلة تمت معاينتها باستخدام المجهر الألكتروني الماسح. وقد وجد أنّ أفضل عملية تشغيل لأوكسيد الزركونيوم ZrO_2 كانت مع المعايير التالية: النحاس الملاصق كقطب مساند، قطبية موجبة لعينة الشغل، معدّل تغذية بمقدار 3 مايكرومتر\ ثانية وعيّنة شغل مغمورة في سائل عازل مع دوران باتجاه واحد. واستخدمت أفضل الظروف في عملية التطوير كمعايير ثابتة. كانت سرعة الدوران وقيمة فرق الجهد هي معلّمات أو معايير السيطرة في عملية تحليل معدّل إزالة المادّة المشغلّة وإعادة صياغة الطبقة. لقد تم حساب نتائج معدّل إزالة المواد من خلال حساب حجم المواد المزالة بالنسبة لوقت التشغيل. وفيما يخص الطبقة المعاد صياغتها فقد تم حساب صلابتها باستخدام إختبار صلابة فيكرز المايكروي. إنّ معدل إزالة المواد وكذلك بيانات الصلابة تم تحليل نتائجها ووضعت لها نماذج تجريبية باستخدام برنامج الخبير التصميمي. وبالنسبة لمعايير تحقيق أعلى معدّل إزالة مواد فقد وجد أنّ أفضل هذه المعايير عندما تكون سرعة الدوران هي 375 دورة في الدقيقة و80 فولت كقيمة لفرق الجهد. في حين أنّ أفضل معايير تحقيق أوطأ صلابة في إعادة صياغة الطبقة هي عندما تكون صلابة فيكرز 874.8 مع سرعة دوران 378 دورة في الدقيقة و110 فولت كقيمة لفرق الجهد.

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 in Manufacturing Engineering.

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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 degrees at IIUM or other institutions.

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LIST OF ABBREVIATIONS

AE	Assisting Electrode
AEM	Assisting Electrode Method
AgW	Silver Tungsten
Al_2O_3	Aluminium Oxide or Alumina
Al_2O_3-SiCw-TiC	Crystaloy 2311EDX Ceramic Composites
ANOVA	Analysis of Variance
Au	Gold
AWJ	Abrasive Water Jet
B_4C	Boron Carbide
Cu	Copper
CuW	Copper Tungsten
DF	Degrees of Freedom
DoE	Design of Experiment
ED	Electro Discharge
EDM	Electro Discharge Machining
EWR	Electrode Wear Rate
HAZ	Heat Affected Zone
LAM	Laser Assisted Machining
MRR	Material Removal Rate
MS	Mean Square
RC	Resistance Capacitance
SEM	Scanning Electron Microscope
Si_3N_4	Sialon Ceramic or Silicon Nitride
Si_3N_4-TiN	Silicon Nitride Ceramic Composite
SiSiC	Siliconised Silicon Carbide
SR	Surface Roughness
SS	Sum of Square
TiC	Titanium Carbide
TiN	Titanium Nitride
W	Tungsten
WC	Tungsten Carbide
WC-Co	Cobalt-bonded Tungsten Carbide
ZrO_2	Zirconium Oxide or Zirconia
ZrO_2-TiN	Zirconia Based Composite

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Electro discharge machining (EDM) process is commonly used in mold and die manufacturing industries (Chen et al., 2009). EDM is known for machining hard and brittle conductive materials (Hosel et al., 2011a, 2011b). A series of electrical sparks or discharges occur rapidly in a short span of time within a constant spark gap between micro-sized tool electrode and workpiece material. The tool and the workpiece are adequately both immersed in a dielectric medium, such as, kerosene, deionised water, or any other suitable fluid (Chow et al., 2008; Chen et al., 2009).

However, non-conductive ceramics have been successfully machined by EDM using the assisting electrode method (AEM) with some modifications done in the process (Hosel et al., 2011a, 2011b; Muttamara et al., 2009; Mohri et al., 1996; Chen et al., 2009). Ceramics such as zirconia (ZrO_2) are used in many applications especially in biomedical field due to their high strength and very low wear. Researchers have turned to EDM to machine ceramics since it is difficult to machine when the conventional cutting techniques are used (Schubert et al., 2009; Hosel 2011a, 2011b).

In AEM, a conductive layer is applied on top of the non-conductive ceramic in order to generate spark between the workpiece and the tool electrode. High temperature around the dielectric fluid will degenerate the polymer chains and creates carbon elements from cracked polymer chains. The carbon elements, together with the conductive debris cover the ceramic surface to sustain the conductivity (Hosel et al., 2011a, 2011b; Liu et al., 2008; Mohri et al., 1996; Muttamara et al., 2009; Fukuzawa et al., 2004).

Material removal rate (MRR) in EDM has been one of the main concerns. The MRR is expressed as the weight of material removed from workpiece over a period of machining time. Many researchers have attempted to develop empirical models to estimate MRR. The MRR depends on the amount of pulsed current in each discharge, frequency of the discharge, electrode material, work material, and dielectric flushing condition (Dave et al., 2012; Somashekhar et al., 2010). Nevertheless, in order to obtain high MRR in ceramic using EDM, high power is needed (Ting et al., 2009; Ji et al., 2011). The material removed in ceramic is mainly by spalling process. Spalling is a mechanism that removes small volumes of material from the base material due to large micro-cracks generated during EDM (Lauwers et al., 2004). This process happens when large amount of energy is directly discharged into the discharge gap during machining (Ji et al., 2011; Hosel et al., 2011a, 2011b).

"Recast" or "white layer" is a thin layer of re-solidified material formed on the workpiece. Recast layer created in EDM process has different properties depending on the electrical energy that consist of voltage, current, time of pulse, and pulse interval. The dielectric properties, its hydrodynamic parameters, and tool electrode have a significant role in determining the surface layer properties (Grzesik et al., 2010; Mehta et al., 2009).

1.2 PROBLEM STATEMENT

Non-conductive ceramics are difficult to machine using EDM as process modification is needed. In addition, this modified machining process has several limitations such as low MRR, limited machining depth, and poor surface quality. MRR is affected by ceramic purity, grain structure, thermal stress, and spalling. Spalling occurs irregularly and is difficult to estimate. As a result, the MRR is found to be inconsistent and its estimation remains as a critical issue.

In addition, recast layer formed on EDMed surface serves as a barrier to obtaining high machining accuracy. The physical and chemical properties of the recast layer are found to be different from the workpiece material. It usually contains several cracks, microcracks, droplets, and globules. It is also unpredictable whether the surface would be brittle or ductile in nature. This layer affects the proper functioning of the original parts. Elimination or minimization of the recast layer by controlling process parameters is another crucial issue which has not been investigated.

1.3 SIGNIFICANCE OF THE RESEARCH

The main concern of this research is to analyze MRR and hardness of recast layer formed during micro-EDM on ceramic material. The developed process will be a breakthrough in determining MRR and recast layer hardness for ceramic product fabrication such as micro tools and molds with minimum tribological issues. The models can be used for machining ceramic and its investigation. The developed process will contribute to the advancement of new knowledge in the field of machining of non-conductive ceramics.

1.4 RESEARCH OBJECTIVES

The objectives of this research are to investigate MRR and hardness of recast layer in micro-EDM of ZrO_2 ceramic. The specific objectives of this research are as follows:

1. To study the machinability of ZrO_2 by micro-EDM using EDM-3 synthetic oil dielectric fluid and tungsten tool electrode.
2. To develop empirical models for MRR and recast layer hardness using the tool rotational speed and gap voltage.
3. To optimize the process parameters for maximum MRR and minimum recast layer hardness in micro-EDM of ZrO_2.

1.5 RESEARCH METHODOLOGY

This research started with literature review and selection of equipment and materials. Zirconia (ZrO_2) was chosen as workpiece material, whereas tungsten as the tool electrode, and EDM-3 synthetic oil as the dielectric fluid. In process development, the work material was prepared and various types of machining setup were used. It is to determine the best condition to machine ceramic by micro-EDM. Detailed explanations on the methodology are discussed in Chapter 3. Once the process development was confirmed, the detail experiments of MRR and recast layer hardness were conducted. The experiments were designed using general factorial of two factors with four levels (4^2) statistical model. Further details on experimental procedure are discussed in Chapter 5. The results were analyzed and optimized using Design Expert version 6.0.8. Once the models of MRR and recast layer hardness were found to be significant, the process moved to the next step which was verification. However, if the analyses were not significant, the processes were revised starting from the experimental step. This process continued until the analyses were found to be significant.

1.6 SCOPE OF RESEARCH

The scopes of the research were as follows:

1. Machining of micro-EDM on non-conductive material using EDM-3 synthetic oil as the dielectric fluid and tungsten as the tool electrode.
2. Only zirconium oxide (ZrO_2) ceramic was used as the workpiece material for machining of non-conductive material using micro-EDM.
3. Results of process development were based on the observation of the SEM images.
4. Use of general factorial method for experimental design.
5. Tool rotational speed (300-600 rpm) and gap voltage (80-110 V) were used and analyzed.

1.7 DISSERTATION ORGANIZATION

Chapter One introduces the background of this research, problem statement, objectives, and scope of the research. Chapter Two, on the other hand reviews different non-traditional machining operations that can machine non-conductive ceramics. A detailed review on EDM of non-conductive materials has been discussed. Chapter Three discusses the overall methodology of process development and investigation of MRR and recast layer hardness. Equipment and materials used are also discussed. Chapter Four provides observation and discussion on process development that fulfils the first objective. Chapter Five shows the design of experiments and detailed experimental procedure to investigate MRR and recast layer hardness. Consequently, Chapter Six provides the results and explanation for MRR and recast layer hardness based on the statistical analysis of micro-EDM process on non-conductive material. Finally, the dissertation concludes in Chapter Seven with some recommendations for future works.

CHAPTER TWO

LITERATURE REVIEW

In this chapter, the non-traditional machining operations of non-conductive ceramics are discussed briefly whereas studies of EDM and micro-EDM operation of non-conductive ceramics are discussed in greater details. Application on zirconia and design of experiment are also briefly touched.

2.1 MACHINING OF NON-CONDUCTIVE CERAMICS

Ceramic materials are commonly and vastly used in many applications such as machine tools, moulds and dies, vehicle systems, electronic devices, semiconductor systems, and in biomedical field. This is due to their material properties which include:

1. 400-1465 MPa strength (Chevalier and Gremillard, 2009; Carden, 2011),
2. 1000-2500 Hv Vickers hardness (Chevalier and Gremillard, 2009),
3. 900-1200 MPa bending strength (Mehta and Shetty, 2010; Hosel et al., 2011a, 2011b),
4. 2050-2720ºC melting temperature (Kucukturk and Cogun, 2010; Mohri et al., 1991),
5. greater than 6 gcm^{-3} density (Mehta and Shetty, 2010),
6. high chemical inertness (Liu et al., 2008a, 2008b; Ji et al., 2011),
7. biocompatibility (Schubert et al., 2011),
8. excellent dielectric strength (Chen et al., 2009),
9. outstanding corrosion resistance (Chen et al., 2009), and

10. very low wear (Liu et al., 2008a, 2008b; Ji et al., 2011).

Aluminium oxide, also known as alumina (Al_2O_3) and zirconium oxide or zirconium dioxide, also known as zirconia (ZrO_2) are commonly used as advanced technical ceramic materials. Yet these materials are difficult to machine due to high brittleness, hardness, and non-electrical conductivity (Chen et al., 2009; Schubert et al., 2011; Liu et al., 2008a, 2008b; Mohri et al., 1991; Ji et al., 2011). The following subsections will discuss different types of non-traditional machining methods for non-conductive ceramics.

2.1.1 Abrasive Water Jet (AWJ)

Abrasive water jet (AWJ) can cut both electrically conductive and non-conductive difficult-to-machine materials. AWJ machining involves a very high velocity of water jet mixed with abrasive particles hitting the workpiece surface which leads to erosion of the work surface. The material removal process occurs due to erosion, shear or failure under rapidly changing localized stress field (Jain, 2008). Water jet pressure, stand-off distance, abrasive type and size, and flow rate are the factors that affect the material removal. These factors are usually affected by machined material structure and geometry of the jet nozzle. Moreover, the machined surface does not have heat affected zone (HAZ) since it yields little heat during machining operation. Other advantages of AWJ are the capability to cut thick materials, at fast speed, with good accuracy, better finishing surface, and cuts virtually without HAZ. However, the drawbacks are burr formation near the cutting area and a large-scale fracture can develope easily on the backside of the surface that affects the surface finish. AWJ also can cause damage to the machined surface due to pits occurrence at the lower zone of the surface that leads to poor surface quality although it is known to be the most efficient to machine ceramics (Ting et al., 2009). Figure 2.1 shows the common nozzle configuration for mixing abrasive with water jet in an AWJ cutting head.

2.1.2 Laser Assisted Machining (LAM)

Laser assisted machining (LAM) is a machining operation that uses laser as a heat source with the beam focused on the surface of the workpiece, as shown in Figure 2.2. Ductile deformation occurs during the cutting process when the heat soften the surface layer. The power requirement depends on the material and the nature of the machining operation. It is capable of cutting non-reflective materials. No burr and little HAZ, resulting from a precise cut with high speed are among the advantages of the LAM process. Moreover, it has the ability to reduce cutting force and lower dynamic forces, producing less segmented chip generation, resulting in a smoother surface finish. Nevertheless, the drawback of this machining operation is that it requires high energy, involves high cost, and must be conducted in special conditions (Ting et al., 2009).

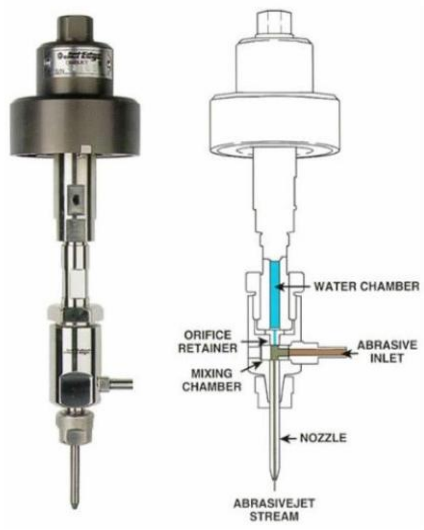

Figure 2.1: Nozzle configuration for AWJ (Abdel-Rahman, 2011).

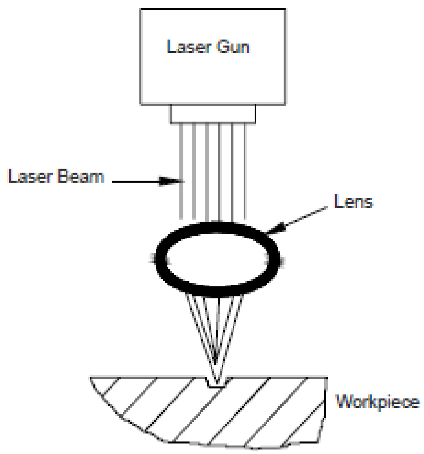

Figure 2.2: LAM schematic diagram (Jain, 2008).

2.1.3 Electrical Discharge Machining (EDM)

EDM is a non-traditional machining commonly used in mold and dies manufacturing industries due to its capability in machining difficult-to-cut and brittle conductive materials (Chen et al., 2009; Schubert and Ziedler, 2009; Chung et al., 2011). It is also used in aerospace and automotive industry as well as in making surgical components (Abbas et al., 2006). The workpiece machined by EDM depends on the thermal conductivity, electrical conductivity, and melting points of the materials (Mohri et al., 1996, 2003; Mahardika et al., 2008). The noncontact nature of the process with nearly force free machining allows soft electrode materials to machine a very hard, fragile or thin workpieces (Jahan et al., 2009; Masuzawa, 2000; Schubert et al., 2013). Hence, due to noncontact nature; mechanical stresses, chatter, and vibration problems during machining can be eliminated (Ho and Newman, 2003).

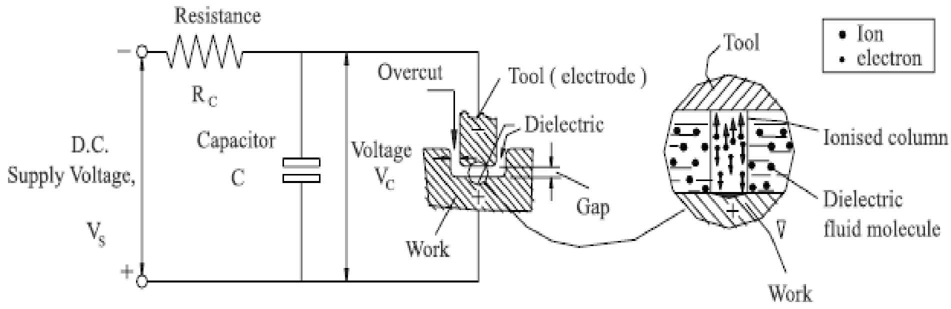

Figure 2.3: Schematic of EDM process (Jain, 2008).

Polarity is a vital factor in this machining as electrical sparks are produced between the workpiece as cathode and electrode as anode or vice versa (Mahardika et al., 2008). In this process electrical spark is created by electrical energy and materials are removed using thermal energy of the spark (Muttamara et al., 2010). The series of electrical sparks or discharges occur rapidly in a short span of time within a constant spark gap between the electrode and workpiece material. The nature of the sparks is repetitive and discrete. The tool and the workpiece are immersed in a dielectric medium, such as kerosene, deionised water, pure water, or any other suitable fluid (Chow et al., 2008; Chen et al., 2009; Singh and Bhardwaj, 2011; Khan, 2011b). The gap between the electrode and workpiece are small enough to produce voltage that ionizes the dielectric (Mahardika et al., 2008). Figure 2.3 shows the schematic diagram of EDM operation.

This process has already been developed in micro scale industries as fine micro tools can machine workpiece surface without deviation or breaking. Micro-EDM follows the similar principle of conventional EDM technology. But, there are some differences between these two machining in terms of circuitry. EDM uses resistance capacitance relaxation (RC-relaxation) circuit meanwhile micro-EDM uses RC-pulse