ENHANCING μ-WEDM AND EDM (WIRE/ELECTRO-DISCHARGE MACHINING) OF DOPED SILICON

BY

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A dissertation submitted in fulfilment of the requirement for the degree of Master of Science in Mechatronic Engineering

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ABSTRACT

Electro-Discharge Machining and Wire Electro-Discharge Machining are nonconventional machining technology which is extensively used for metal based fabrication process. This process enables machining of any material, which is electrically conductive, irrespective of its brittleness, hardness or strength, therefore conductive material is usually easy to machine by µ-WEDM and µ-EDM. Si which is the workpiece in this research is a semiconductor material with high resistivity and it is difficult to machine by µ-WEDM and µ-EDM. Thus, the machining of Si can be enhanced if it is possible to increase the conductivity of this semiconductor. This study aims develop and characterize the process of enhanced µ-WEDMing and and µ-EDMing of Si by temporary coating this Si with a high conductive metal (gold in this study). The methodology of this work started with the coating the Si workpiece with gold (Au) using sputter machine. Then µ-WEDMing and µ-EDMing processes were carried out. The workpiece samples prepared for characterization through cleaning these samples by ultrasonic machine. The characterization was carried out using the Scanning Electron Microscope (SEM) machine. WEDM process stability was found to be improved (up to 60 times for certain machining condition) if coated Si wafer is used as compared to uncoated Si workpiece. Material removal rate was also found to be increased by a good margin (~ 30% average) for coated Si wafer. Machined slots were found to be more uniform though kerf width was slightly larger for coated Si wafer. In the case of EDM, the process stability for coated Si was found to be more stable than uncoated Si especially for high discharge energy. MRR for gold coated silicon samples was higher than uncoated silicon sample (about more than 10 x for 85V and 10 nF machining condition). Overall this new method of µ-WEDM and µ-EDMing operations of polished Si wafer has been found to be more efficient and useful. Removal of the conductive coating without damaging the substrate is a challenge for this process which was carried out successfully by selective etching method.

ملخص البحث

التشغيل بالتفريغ الكهربائي وتشغيل القطع بالتفريغ الكهربائي هي تقنية تشغيل غير تقليدية تستخدم على نطاق واسع من أجل تشغيل المعادن. يمكن لهذه الطريقة تشغيل أي مادة موصّلة كهربائياً بغض النظر عن كون هذه المادة هشة، صلبة أو قوية. أي أنّ المواد الموصّلة كهربائياً يمكن تشغيلها بطريقة التفريغ الكهربائي بسهولة بفرعيها التفريغ الكهربائي والقطع بالتفريغ الكهربائي. على كل حال فإنّ السليكون الذي هو المادة المشغلة في هذا البحث يعد مادة شبه موصّلة ذات مقاومة كهربائية عالية تجعل من الصعب تشغيل هذه المادة بواسطة التفريغ و القطع بالتفريغ الكهربائي المايكروي. وبهذا يمكن تحسين تشغيل السليكون عن طريق زيادة موصليّته. تهدف هذه الدراسة لتطوير وتوصيف عملية تحسين تشغيل السليكون بالتفريغ والقطع بالتفريغ الكهربائي المايكروي عن طريق طلاء مؤقّت لهذا السليكون بمعدن ذو موصليّة عالية (الذهب في هذه الدراسة). منهجية العمل في هذا البحث بدأت بعملية طلاء مؤقتة للسلكون بمادة الذهب ذات الموصلية العالية باستخدام آلة رش خاصة بذلك ثم أجريت عمليات التفريغ الكهربائي. وقد أعدت عينات الشغل للتوصيف وتسجيل النتائج من خلال تنظيف هذه العينات من خلال استخدام جهاز الموجات فوق الصوتية وتلتها عملية التوصيف باستخدام جهاز مجهر المسح الضوئي. وقد وجد أن إستقرارية عملية تشغيل القطع بالتفريغ الكهربائي تتحسن بشكل كبير (تصل إلى ستين ضعف في بعض حالات القطع) كمقارنة بين رقائق السليكون المطليّة بالذهب وغير المطليّة. كما وجد أن معدّل التشغيل يزداد بهامش جيد (بمعدّل حوالي ثلاثون بالمائة) لعينات الرقائق الطليّة. وقد لوحظ أن نسق فتحات القطع منتظمة أكثر على الرغم من أن عرض الشق في هذه الفتحات أكبر قليلاً كنتيجة لعمليّة الطلاء بالذهب وارتفاع الموصليّة الكهربائية. وفيما يخص التشغيل بالتفريغ الكهربائي (الإعتيادي وليس القطع) فإن استقرارية التشغيل للمشغولة المطلية بالذهب أفضل خاصةً التشغيل في ظروف الطاقة العالية. كما أن معدّل إزالة المادة للعيّنات المطلية أعلى بكثير من العينات غير المطلية (حوالي 10 أضعاف في ظروف التشغيل للطاقة 85 فولت و10 نانو فاراد). عموماً فإنّ هذه الطريقة من التشغيل تكون ذات فائدة وكفاءة أعلى. عملية إزالة طلاء المادة الموصلة دون الإضرار بركيزة الشغل الأساسية (أي عينة السليكون) يشكّل تحدّياً في هذا العمل والذي نفّذ بنجاح بطريقة إنتقائية.

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 (Mechatronics Engineering)

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DECLARATION

I hereby declare that this dissertation is the result of my own investigation, 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.

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LIST OF ABBREVIATIONS

AU	Gold
CNC	Computer Numerical Control
EDM	Electro-Discharge Machining
EDX	Energy-Dispersive X-Ray Spectroscopy
FMSEM	Field Emission Scanning Electron Microscope
H2O	Water
HCL	Hydraulic Acid
HNO3	Nitric Acid
MRR	Material Removal Rate
WEDM	Wire Electro-Discharge Machining
SEM	Scanning Electron Microscope
SI	Silicon
SR	Surface Roughness
TWR	Tool Wear Ratio

LIST OF SYMBOLS

µ	Micro
Req	Equivalent Resistance of the Au-Si-Au Composite
ρ_{Au}	The Resistivity of Gold Coating
ρ_{Si}	The Resistivity of the Silicon Wafer
L	The Workpiece Length
A_{Au}	The Cross Sectional Area of the Gold Coating
A_{Si}	The Cross Sectional Area of the Silicon
K1	A Multiplying Factor and Its Value Is $0<K1<1$
K2	Another Factor and Has Value between $0<K2<\infty$

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Machining is a regulated material removal process from a piece of raw material. The objective of this process is to produce final product with proper shape and controlled dimension from the workpiece (raw material). The boundary of "machining" has grown as technology has advanced. Machining is one of the main technologies that is used for producing many metal products. However the use of machining is extended to other materials such as wood, plastic, ceramic, and composites. In general, the place where machining is carried out is known as machine shop or shop floor. A machine shop encompasses one or more work chambers/ work areas that surround the machine tools. A machine shop can itself be a standalone business to produce finished products for the market or it can play an internal supporting role for a bigger industry. In order to manufacture product with desired dimension and proper tolerance as specified in the design documents, several things need to be considered during machining such as, tool material, workpiece material, type of machining process etc. Relative motion between the tool and workpiece is the primary reason behind all machining process that causes material to be removed from the workpiece, however tool shape and tool penetration into the workpiece are also responsible for this. Relative motion between the tool and workpiece is achieved by the combined action of the primary motion called '<u>cutting speed</u>' and secondary motion called '<u>feed speed</u>'. Modern days' machining process is mostly carried out by Computer Numerical Control (CNC) machine in which software based automatic control system carries out the movement and operation of the machine tools.

Machining processes can be divided into mainly two groups "Conventional Machining Processes" and "Non-Conventional Machining Processes". Turning, boring, milling, shaping, broaching, slotting, grinding etc fall under the category of conventional machining process. Similarly there are several examples of non-conventional machining such as Abrasive Jet Machining (AJM), Electro-discharge Machining (EDM), Electro-chemical Machining (ECM) and Ultrasonic Machining (USM) etc. In conventional machining usually harder material is used as tool for changing the shape of a workpiece by cutting operation. Machining hard metals and alloys using conventional methods involves longer time and higher energy, and therefore, an increase in costs. Conventional machining may also higher tool wear and deteriorated quality in the product owing to induced residual stresses during manufacturing. Conventional machining can be defined as a process of using mechanical (motion) energy. On the other hand, most non-conventional machining has no direct contact between the tool and workpiece. It has several other features and the three main forms of energy that are used in these processes are thermal energy, chemical energy and electrical energy. If one asks why we need the non-conventional machine? The simple answer is, in several industries, hard and brittle materials like tungsten carbide (used for making cutting tools), high speed steels (used for making gear cutters, drills, milling cutters), stainless steels, ceramics etc. are often used. If such materials are machined with the help of conventional machining processes, either the tool undergoes extreme wear (in case of hard materials) or the workpiece material is damaged (in case of brittle materials). This is because, in conventional machining, there is a direct contact between the tool and the workpiece. Large cutting forces are involved, and material, are removed in the form of chips. A huge amount of heat is produced in the workpiece. This induces residual stresses, which degrades the life and quality of the workpiece material. To overcome all these drawbacks, non-conventional machining processes are used to machine hard and brittle materials. As well as to machine soft materials, in order to get better dimensional accuracy. The best way to give a clear vision of these two machining groups (conventional and non-conventional) is to introduce a comparison between them. In conventional processes generally macroscopic chip formation by shear deformation. While material removal may occur with chip formation or even no chip formation may take place in non-conventional processes. Back to conventional processes, there is a physical tool present such as a cutting tool in a Reamer Machine. While there may not be a physical tool present in non-conventional processes such as in laser jet machining. Again in conventional machining the tool should be harder than the workpiece under the machining conditions. While as mentioned in the above, there may not be a physical tool present in non-conventional machining. There are number of cases where conventional machining involves lower accuracy and surface finish than the non-conventional machining. Tool life in the conventional might be less than the non-conventional (e.g ECM) due to high surface contact and wear. In the conventional, there are always noisy operations that cause sound pollutions. While there are no sound pollutions in the non-conventional machining. Conventional machining (unlike the non-conventional machining) requires lower capital cost and simple set-up of equipment. Skilled or un-skilled operator can run the conventional machining, while only skilled operator can run the non-conventional that generally operates using automated processes.

Electrical discharge machining (EDM) is an important non-conventional manufacturing method that was developed in 1940s. It has been accepted worldwide as a standard process in manufacturing of forming tools to produce plastics moldings, castings, press tools, forgings, etc. The origin of electrical discharge machining goes back to 1770. An English scientist Joseph Priestly discovered the erosive effect of electrical discharges (Sanjeev, Rupinder, T.P., & B.L., 2009). Later in 1943, Russian scientists B.R. and N.I. Lazarenko at Moscow University had the idea of exploiting the destructive effect of an electrical discharge (Sanjeev, Rupinder, T.P., & B.L., 2009). They also were behind developing a controlled process for machining materials that are conductors of electricity. The Russian scientists perfected the electrical discharge process. The process consisted of a succession of discharges that took place between two conductors separated from each other by a film of non- conducting liquid, called a dielectric. However, it was only in the 1980s, with the advent of Computer Numerical Control (CNC) in the EDM that brought about tremendous advancement in improving the efficiency of the machining operation. This process enables machining of any material, which is electrically conductive, irrespective of its hardness, shape or strength. The EDMing process is very complex and stochastic in nature. More than one discipline is involved in this single machining process, such as electrodynamics, electromagnetic, thermodynamic, and hydrodynamic. Difficulty arises in developing a comprehensive process model for EDM because of its multidisciplinary nature. In the EDM process, material is removed by action of electrical discharge between the tool and the workpiece. The basic principle of the machining is a process when the material of the workpiece is removed through high frequency sparks between the tool (electrode) and the workpiece immersed into the dielectric fluid like oil, de-ionized water etc. But talking about very low energy (in μ-joule range) to create these sparks lead to call of the process as μ-EDM. This μ-EDM is a promising machining technology to produce features in micron domain for different engineering applications. The main difference between conventional EDM and μ-EDM lies in the level of discharge energy and size of the tool used during the operation. In μ-EDM very low discharge energy with high frequency is used (~μ-Joule). Further, typical tool and feature size in μ-EDM are in order of less than or equal to 100 μm.

As applications grow in complexity and shrinking in size of the finished product, micro-machining started to evolve widely. Micro-machining is related to specific techniques applied to micro-scale elements. It produces components with high precision and very restrictive dimensional and geometrical tolerances (micron). CNC machining used to produce small, intricate mechanical components with conventional machining methods on a miniaturized scale. Micro-Grinding is an example of conventional micro-machining which is the art of grinding particles that are tiny in size. Micro-Milling is another example which has different applications such as colloid mills, bead mills, disc mills and jet mills etc. Non-conventional machining can produce micro-products also. Laser machining as a non-conventional process has accuracy for cutting and high precision machining any size. Micro-EDM (this research issue) is one of the most important non-conventional micro-machining processes, it has ability to achieve micro scale and complex shapes.

Wire electrical discharges machining (WEDM) is the variant of EDM based method for non-contact machining. WEDM is a type of EDM operation where the cutting tool is a rotating wire spool and the electric discharge energy is applied between the wire and the workpiece. WEDM is widely used for electrically conductive materials because of its physical nature of operation. The WEDM depends on three basic elements which are wire, workpiece and dielectric fluid as shown in Fig. 3.12 in chapter three. The WEDM process can also be carried out in micron domain with wire size below 100 μm of diameter.

After this background about the mainly two machining groups (conventional and nonconventional), the chapter introduces the micro range of these machining processes, as well as brief details about the EDM technique. For instance how to improve μ-EDMing process based on silicon (Si) as a workpiece of this machining. Silicon (Si) is one of the most common materials on earth. It has advantages for optics over traditional mirror substrate materials. Primarily, due to its thermal and dimensional stability, it is more suitable for high performance applications. Si has several important applications (Infrared sources, detectors, microelectronics and layered fluidic devices) that lead to use this material in the machining. In this electronic era is that Si is considered to be one of the most intensely studied and developed material in manufacturing. The fabrication process for Si by etching method is highly mature. However, machining Si by EDM has several advantages compared to the more traditional techniques. Firstly, it requires a low installation cost. Secondly, shapes that difficult to be machined by etching are relatively easy for the EDM. That is why Si has been chosen as the workpiece of μ-WEDMing in this study. Si is a semiconductor material, so it is difficult to machine by WEDM because of its high resistivity. The high resistivity or the low conductivity of Si prevents somehow the free electrons doing electrical discharge process. Therefore, the machining of Si can be enhanced if we succeed to increase the conductivity of this semiconductor. Si conductivity may increase by coating it with a high conductive metal such as copper, silver or gold; WEDM becomes more effective as the conductivity of the workpiece increases. Therefore, in this research a new method of μ-WEDMing of Si workpiece is proposed. The workpieces were coated with different thickness of gold before machining in order to enhance the machining. Then record the results and discover the appropriate machining conditions for different samples (Si without coating and Si with different coating layers). The strategy here is fabricating temporary coating for this Si with a high conductive metal (gold in this project), and doing the µ-WEDMing. Then remove the coating layers after finishing the machining process by selective chemical method without damaging the substrate (original Si workpiece).

1.2 PROBLEM STATEMENT AND ITS SIGNIFICANCE

µ-WEDM uses very low energy for creating the spark in the gap between the tool (wire) and the workpiece in the dielectric. The spark achieves the machining (material-removal) when the µ-WEDM process reaches to the peak current. This process (reaching to the peak current) requires good conductivity of the three principle elements (tool, workpiece and dielectric). Silicon (our workpiece in this µ-WEDMing) is a semiconductor and has higher resistance compared to normal conductor. Therefore, it is difficult to machine Si by the WEDM which is supported by earlier work (Bo-Huai, Hsiang-Kuo, Yang-Xin, Shi-Jie, Fuang-Yuan, & Biing-Hwa, 2009). In order to overcome this problem we propose to coat the Si workpiece to increase its conductivity during machining, so that the µ-WEDMing performance for Si can be enhanced.

As it was mentioned earlier, gold (Au) is the metal that has been chosen to coat Si (according to the facilities of that we found in the university) in order to increase its conductivity. But we need later after µ-WEDMing to remove these layers of gold to get the original substrate (Si) without damaging; in fact, this is another big challenge because the gold is one of the strongest metals which are not removed easily.

1.3 RESEARCH OBJECTIVES

In order to address the problem of machining Si by as stated in section 1.2, this research aims for the following objectives:

1- To develop an electrical equivalent process model for µ-WEDM and µ-EDM of gold coated Si workpiece.

2- To experimentally verify the improvement of the proposed µ-WEDM and µ-EDM method.

3- To characterize the process parameters such as material removal rate (MRR), machining stability, morphology study of the finished product etc.

1.4 SCOPE OF RESEARCH

Wire electrical discharge machining (WEDM) is a non-conventional machining process. This process enables the machining of any material, which is electrically conductive. Several procedures involve in this research to achieve the machining process. These procedures start by coating the workpiece material, which is doped silicon (Si). The reason behind this is to increase the conductivity of Si which is a semiconductor, and has a high resistance. That µ-WEDMing requires good conductivity of the machining elements (tool, workpiece and dielectric). The research is concerned with characterization of the machining result for gold coated Si. It is also concerned with removal the coating (gold) layers from the workpiece after finishing the µ-WEDMing process to obtain the original workpiece material (Si).

1.5 RESEARCH METHODOLOGY

To achieve the objectives of this research, the research methodology depended on several steps. The research started with literature review of technical and scientific papers on related works of electrical discharge machining (EDM). The workpiece (Si) was coated with different gold layer thickness using Sputter Coater machine in order to increase its conductivity for µ-WEDMing. Then the most important step was the experimentation on the EDM process by CNC machine (mikrotools) which has a wire-cut and other components required to achieve the µ-WEDMing, this operation was carried out using a 3-axis multipurpose machine tool. Results can be obtained by cleaning the workpiece samples through using acetone and ultrasound machine. Moreover, Scanning Electron Microscope (SEM) was used for characterization of surface roughness. SEM was also used for the measurement of the kerf width of the machined slots. After finishing the experimentations, a chemical solution (HCL : HNO3 : H2O) was used with ratios (1 : 0.16 : 1) respectively, to remove the coating (gold) without damaging the original Si workpiece. Then Energy-Dispersive X-ray spectroscopy (EDX) technique was used also to ensure that there is no more gold on the substrate surface.

1.6 THESIS ORGANIZATION

This thesis is organized in five chapters. Background of the EDM, problem statement and research objectives are all presented in chapter one. Literature review of technical and scientific papers on related works of the EDM are discussed in chapter two. Theoretical background and the methodology of implementing the work, including the details of all machines involved in the experimentations are introduced in chapter three. Then chapter four presents the results and discussion. It also presents the performance analysis for our workpiece samples and produces some actual applications of this work. Finally chapter five shows the conclusion and possible recommendations for related future works.