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A Study on the Micro Electro-Discharge Machining of Aerospace Materials

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A STUDY ON THE MICRO ELECTRO-DISCHARGE MACHINING OF AEROSPACE MATERIALS

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Date

I would like to dedicate this thesis to my family: my mother Brenda Moses, my father Michael Moses and my sister Britta'ny Moses. Without their constant prayers, encouragement and support, I would not be able to achieve the success in completing this chapter in my graduate career.

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Electrical Discharge Machining (EDM) is a non-traditional machining process that uses hundreds of thousands of minute electrical sparks per second to machine any electrically conductive material, no matter the hardness or how delicate it is. EDM allows a much greater range of design possibilities, unconstrained from the traditional machining processes, in which material is removed mechanically by either rotating the cutting tool or the work piece. Shapes that were impossible to machine by any other method, such as deep, precision, square holes and slots with sharp inside corners, are readily produced. It provides accurate geometries in high- aspect ratio holes and slots, blind undercuts, small holes adjacent to deep sidewalls, and complex cuts in thin, fragile parts. Micro-EDM is a growing form of manufacturing and will continue to expand within various production fields. Micro-EDM is especially attractive for the applications where the cutting time is minimal, but precision and accuracy are maximized. Micro-EDM is a non-traditional cutting process, which consistently produces ultra-precise holes with fine surface finishes and better roundness, while holding extremely close diameter tolerances. The process could be an excellent problem-solving tool for configurations that are difficult or impossible to produce using conventional machining processes.

This study presents a comparative experimental investigation on the micro-EDM machinability of difficult-to-cut Ti-6Al-4V and soft brass materials. As both materials are electrically conductive, they were machinable using the micro-EDM process irrespective

of their hardness. The machining performance of the two materials was evaluated based on the quality of the micro-features produced by the micro-EDM process. Both blind and through micro-holes and micro-slots were machined on brass and Ti-6Al-4V materials. The quality of micro-features was assessed based on the shape accuracy, surface finish and profile accuracy of the features. Finally, the arrays of micro-features were machined on both materials to compare the mass production capability of micro-EDM process on those materials.

Introduction

Background

The origin of the EDM process can be traced as far back as 1770, when an English chemist named Joseph Priestly discovered the erosive effect of electrical discharges or sparks (Ho & Newman, 2003; Puertas & Luis, 2004). In the 1930s, various attempts were made to machine metals and diamonds with electrical discharges. Electrical Discharge Machining (EDM) has since become a well-established machining process for the manufacturing of complex cavities in dies and molds or hard material parts that are extremely difficult to machine by conventional processes. One distinction of EDM is that it does not make direct contact between the electrode and the work-piece. This is believed to eliminate mechanical stresses and vibration during machining.

EDM is the thermal erosion process in which metal is removed by a series of recurring electrical discharges between a cutting tool acting as an electrode and a conductive work-piece (material), while a dielectric fluid is being introduced. This discharge occurs in a voltage gap between the electrode and work-piece. The heat generated from the discharge vaporizes the tiny particles of the work-piece material, which are then washed from the gap by the continuously flushing of dielectric fluid. EDM is mainly used to machine difficult-to-machine materials and high strength temperature resistant alloys. Work material to be machined by EDM has to be electrically conductive. The selection of optimum machining parameters in EDM is an important step. Improperly selected parameters may result in serious problems like short-circuiting or acting, wire/tool breakage and work surface damage, which impose certain limits on the production schedule and also reduce productivity. As material removal rate (MRR) and surface roughness (Ra) are most important responses in EDM, selection of optimum parameters greatly depend on those performance parameters (Ho & Newman, 2003).

The titanium alloy is considered a rather new material used in the market for manufacturing purposes. In a relatively short period of time it has become one of the essential metals for aerospace and automotive industries. The use of titanium alloy in various engineering fields is due to its high specific strength, high temperature strength within a broad temperature range, and high corrosion resistance (Jilani, 2014). Also, comparing it to other metal, titanium has lower values of thermal conductivity, electrical resistance and thermal expansion. Titanium alloy has exhibited excellent technical properties, especially in term of strength, hardness and toughness (Jilani, 2014).

In an effort to achieve certain weight reduction and increased thermal efficiency of jet engines, the use of "hard to machine alloys" such as Titanium, Ti-6Al-4V and Inconel 718 are common for the manufacture of aero engine components. The milling process of blisks made of Titanium-based alloys has reached its technological and economical limit. In this instance, Electrical Discharge Machining (EDM) is a cost-effective alternative. The major outputs of an EDM process are material removal rate (MRR) and surface integrity of the work-piece. Research has been carried out to improve the efficiency and effectiveness of this machining process towards enhancing these outputs. Studies are ongoing for the use of numerical modeling to gain improvement in process variables of both die sinking EDM and micro-EDM. Since micro-EDM is one of the main techniques used in processing of this material, the possibility of improving it is important.

Several investigations have shown that the machining by Electrical Discharge Machining (EDM) process is more efficient on the surface of machined parts versus several other machining technologies. The importance of this study was to test the feasibility of machining of Titanium alloy using micro-EDM process compared to the micro-EDM of soft brass materials. The micro-EDM performance was evaluated by measuring the dimensional accuracy, surface integrity, and elemental composition.

Problem Statement

Titanium is a metal alloy that has integrated itself within many engineering challenges presented today in the aerospace industries, as it can be exposed to very high temperatures and high corrosion resistance. A similar material that can be compared, in order to fully understand feasibility and functionality, would be steel. Titanium is 30% stronger than steel and almost half its weight. Aluminum is another metal that can be compared to titanium, but titanium alloy is twice as strong and 60% heavier. Titanium, like steel and aluminum, can be used in a multitude of applications. (Jilani, 2014)

Even with titanium being such a valued resource in aerospace materials, it does have one major problem. Titanium is very difficult to machine due to its hardness. This is the main reason that the titanium market is such a finite one, which usually has very specific and unique uses. There are various ways that titanium has been machined. They include: turning, boring, milling, sawing, water jet, tapping, grinding, chemical milling, and electric discharge machining. Most of these processes are different in nature, but they all contain the same end goal and deal with the same problems of the titanium piece. Titanium alloy (due to its hardness) is difficult to machine using those conventional machining processes. (Guo, Li & Jawahir, 2009). Therefore, this research looked to help continue to solve the best way to manipulate and machine titanium alloy through the use of micro electrical discharge machining (micro-EDM) process.

Significance and Purpose

The growing use of EDM systems in manufacturing allows for new innovative forms of metal and material manipulation. The areas of electrical discharge machining are not confined to aerospace any longer. This is the cause for more studies to be conducted to optimize the process and allow more feasible ways to increase the overall productivity of manufacturing by increasing the types of materials utilized. This can lead to new merchandise and longer durability of those products because of their material and elemental makeup. Therefore, it is important to study the micro-EDM performance of aerospace materials like Ti-6Al-4V, as it could open the possibility of using this material for more innovative applications.

Hypotheses

The micro-EDM process will be able to machine micro features in Ti-6Al-4V with the quality needed in machined surface and with desired dimensional accuracy. The expectation is that for both the soft and hard material work pieces, the machined features have an acceptable surface finish and quality. This will endorse the continued and increased use of the micro-EDM process as the uses expand in various areas of manufacturing.

H1-The titanium alloy will be sufficiently manipulated by the micro-EDM process in regards to the overall quality of the holes and slots.

H2- The through holes in the titanium alloy will contain more debris than the through holes of brass due to the hardiness of the material

H3- The blind holes of titanium alloy will contain a larger debris build up than the brass blind holes.

H4- The through slots on the titanium alloy will have a significant amount more debris left over from the machining process due to the material being more difficult to manipulate.

H5- The blind slots on the titanium piece will not be as clean as the blind slots on the brass alloy due to the properties of the titanium alloy.

Assumptions

This study acknowledges that neither the brass nor titanium alloys will have any complications with machining, as EDM and micro-EDM processes are created to machine and manipulate electrically conductive metals. Therefore, both will result in findings that will be easily comparable.

Delimitations

The delimitations that are associated with this study were the varying materials or work pieces involved. These are brass and titanium work pieces. The second delimitation was the number of work pieces to be machined and compared. The research only provided two sources to gather results from, as to have a one-on-one comparison to match with the titanium work piece. The third delimitation is the specific procedure was followed exactly in each of the machined pieces. This ensured that the only change would be based on the materials being analyzed.

The limitations of this research were confined by the EDM setup itself. This study used a micro-EDM system. This is opposed to a standard EDM or WEDM set up. No other elements or forms of EDM were used in comparison or in combination with the micro-EDM arrangement.

Definition of Terms:

- EDM - Electrical Discharge Machining
- Micro-EDM – Micro-electrodischarge Machining
- SEM - Scanning Electron Microscope
- EDS – Energy Dispersive X-ray Spectroscopy
- Titanium - is a chemical element with the symbol **Ti** and atomic number 22. It is a lustrous transition metal with a silver color, low density and high strength (Dictionary.com)
- Brass - is an alloy made of copper and zinc; the proportions of zinc and copper can be varied to create a range of brasses with varying properties. (Dictionary.com)
- WEDM - Wire Electric Discharge Machining
- Spark Gap - consists of an arrangement of two conducting electrodes separated by a gap usually filled with a gas such as air, designed to allow an electric spark to pass between the conductors. When the voltage

difference between the conductors exceeds the gap's breakdown voltage, a spark forms, ionizing the gas and drastically reducing its electrical resistance. (Puertas & Luis, 2009).

- MRR - Material Removal Rate
- Electrode Tool - The small rod in which the electric pulse passes through from the generator to the work piece across the spark gap.
- RSM - Response Surface Methodology explores the relationships between several explanatory variables and one or more response variables.
- Dielectric Fluid - is a dielectric material in liquid state. Its main purpose is to prevent or rapidly quench electric discharges. Dielectric liquids are used as electrical insulators in high voltage applications, e.g. transformers, capacitors, high voltage cables, and switchgear (namely high voltage switchgear). Its function is to provide electrical insulation, suppress corona and arcing, and to serve as a coolant. (Britannica Encyclopedia)
- TWR- Tool Wear Rate
- OC – Overcut
- EDX- Energy Dispersive X-Ray Analyzer (EDX) is also used to provide elemental identification and quantitative compositional information. (Scanning Electron Microscopy with Energy Dispersive X-Ray Analysis, 2014).

Review of Literature

EDM of Titanium Alloys

In the die-sinking EDM, the work-piece can be formed, either by replication of a shaped tool electrode or by three-dimensional (3-D) movement of an electrode similar to milling. The electrode is normally made of copper or graphite. Titanium alloys are very highly regarded for their strength-to-weight ratio above all properties. Because of this, it is commonly used in aerospace and automotive industries. In addition to strength, the higher electrical conductivity of the titanium alloys made them strong candidates to be machined by EDM and micro-EDM process (Klocke, Welling, & Dieckmanna, 2011). Kumar, Singh, Batish and Singh (2012) worked collectively to look into the general process of EDM and the effects it has on high strength temperature resistant (HSTR) titanium alloys. A potential way to optimize the process was the use of cryogenic treatment. This is done because the cryogenic technique improves many of the physical and mechanical properties in metals. Their conclusion was a realization that titanium can be machined with use of an EDM process. This resulted in a better understanding of the EDM process and its manipulation of titanium for various uses.

Once the process had been specifically adapted for machining the titanium alloy, the next step was to find a way to increase the overall efficiency of the process and to produce quality results in the finished product. Pradhan, Masanta, Sarkar and Bhattacharyya (2008) worked with micro EDM of titanium to successfully come up with parameters that would lead to optimum performance in regards to the machining of titanium alloy. To verify those parameters, the basis of their experiment was set up around material removal rate, tool-wear rate, over cut, and taper of the machined area.

Each test was run three times to ensure quality and to create an average baseline from which each of the settings could be accurately monitored and recorded. The conclusion was that there is a higher MRR and TWR when the peak current is increased. With this study, new knowledge will be genereated on the tool wear ratio and how it affects the work-piece. The ongoing attempts to optimize the parameters for machining of titanium alloy promoted the advancement of technology in aerospace industries.

Tiwary, Pradhan and Bhattcharyya (2013) completed a study on EDM of titanium alloy. They developed a mathematical model based on the performance criteria (MRR, TWR, OC) for the machining of titanium alloy. They used RSM (Response Surface Methodology), which is a technique that shows the comparison and exploration of the varying machining criteria. The models estimated results that were very close to the experimental results.

Titanium alloy, being a difficult-to-cut material, suffers poor machinability for most cutting operations, mostly for the drilling of micro-holes when traditional machining methods were being used (Guo, Li & Jawahir, 2009). EDM is suitable for machining titanium alloys, but the selection of machining parameters for higher machining rate and accuracy is more challenging when machining micro-holes. Research attempts to optimize micro-EDM process parameters for machining Ti-6Al-4V super alloy. The performances were affected by the peak current and pulse-on time, during micro-electro-discharge machining of titanium alloy (Mitra, Paul, Sarkar & Nagahanumaiah, 2013).

There have been great successes along with excellent research on nickel–titanium shape memory alloy (NiTi-SMA) when used in reconstructive surgery, but there are still serious concerns and limitations to the clinical applications of NiTi alloy today. (Alidoosti, Gharfari-Nazari, Moztarzadeh, Jalali & Mozafari, 2013). One such concern is the potential leakage of elements and ions during surgery could be toxic to human cells, tissues, and organs. This discussion was around the properties, clinical applications, corrosion performance, biocompatibility and the possible preventive measures to improve corrosion resistance by surface/structure modifications in these metals and other long-term challenges.

Surface Integrity

Although the overall goal of EDM and micro-EDM is to successfully machine or manipulate high-strength and heat-resistant materials that are electrically conductive, the machining performance of the process is very important. Today, the surface integrity of the material after machining is just as important as the overall machining process. Researchers have explored this aspect through SEM (scanning electronic microscope) imaging that the topography and surface roughness were being affected by the conditions of current and pulse duration during the EDM process (Ndaliman, Khan & Ali, 2011). The lower currents produced small cracks with little to no craters, opposed to the higher peak currents that did not result in more cracks, but rather a higher number of craters. This is caused by the intensity of the spark discharges. The surface roughness followed a similar pattern. This study by Ndaliman et al. (2011) also concluded the existence of carbides and oxygen during the process of machining.

The dominant factors were based upon the current and pulse duration. A direct correlation between the intensity and the topography and surface roughness was the final conclusion of their results. Various parameters of EDM were studied in this writing. By using design-of-experiment techniques, these parameters were obtained to get better surface finish on the titanium alloy (Ti-6AL-4V). The adequate selection of manufacturing conditions was one of the most important aspects to take into consideration in the die-sinking electrical discharge machining (EDM) of conductive materials. The input parameters selected for the experimental study were current, pulse on time, and pulse off time. The response parameter that was studied in this test was surface roughness. On the basis of input and response parameters, an orthogonal array "L9" was used for the statistical analysis (Ndaliman et. al., 2011).

Often Ti-6Al-4V is employed in turbine industry components due to its exceptional mechanical properties. The strong mechanical properties make it hard to machine with conventional processes like broaching, milling, or grinding. Wire EDM (WEDM) represents an alternative process to machine this material (Basil, Paul, & Isse, 2013). The comparison between grinding and WEDM of Ti-6Al-4V concerning surface integrity aspects was analyzed and proven by fatigue bending (Basil et. al., 2013). In contrast, the machined specimen showed higher fatigue strength. Subsequent tests of surface integrity aspects have been conducted to continue analysis of the fatigue result. One goal was to have a visual user-friendly quality check that would reflect or correlate the fatigue strength of the EDMed parts. The study done by Garg, Singh, Sachdeva, Sharma, Ojha and Singh (2010) also suggested that WEDM is an alternative to conventional processes for machining titanium alloys.

Material Removal Rate and Tool Wear Rate

It is important to investigate the TWR (tool wear rate) versus the MRR (material removal rate) and how the machining allows them to occur. The most common tool materials used in the EDM process are copper and graphite. This can be attributed to the great thermal and electric properties of the materials. These qualities are found to be abundant in graphite (Morgan, Vallance & Marsh, 2007). Throughout the EDM process, the amount of heat that is generated through the pulse generator causes not only the material to be machined, but also has adverse effects on the actual tool pieces as well. The study by Klocke, Welling and Dieckmanna (2011) would help shed light onto the causes for this. They also investigated to optimize the effect so that there can be a reduced number of electrodes used and the overall cost efficiency to be increased. What was found through this was that the discharged current is the most direct cause for MRR and that the discharge duration is the main factor contributing to the tool wear rate. Keeping this in mind, the two materials used provided vast differences in the tool wear and MRR. Pradhan, Masanta, Sakar and Bhattacharyya, (2008) also brought attention to this matter in their study on micro-EDM, echoing the same results.

Dielectric Fluid

In the pursuit of a set of parameters that would indeed optimize EDM process to produce the best quality results will naturally have variation depending on the tool material and material of the work-piece. With this said, there seems to be a common result in regards to the MRR and TWR. Lajis, Radzi and Amin (2009) reported similar results, showing that the peak current and the pulse duration are the foci for the MRR, SR, and TWR. The use of various electrode tools and the differing materials used as a work-piece can provide various results, but can also be separated again through the use of the dielectric fluid used. An effective EDM process involves using the tool electrode that is separated by a small gap from the material work-piece, where the dielectric fluid presents. Kibria, Sarkar, Pradhan, and Bhattacharyya (2010), understanding this, ran a comparative study with a series of different dielectrics to compile and reveal the changes they have on the MRR and TWR. The varying dielectrics were kerosene, de-ionized water, boron carbide powder, and suspended kerosene. The performance criteria studied were OC (overcut), diametrical variance at the entry and exit holes, along with the overall surface integrity. The rationale for this study was the premise that the type of dielectric plays a large role in the overall performance of the EDM process. There are differences in the chemical composition, viscosity, and cooling strengths in varying fluids, which can all change the results. These researchers used micro-EDM with titanium alloy to compare each dielectric. The results were able to show the full degree that the dielectric fluid had on the performance criteria of the micro-EDM process. SEM imaging was used to show the visual differences in TWR, MRR, OC, microhole accuracy, and dimensional variance at both the entry and exit sides. In many cases of EDM study and research, it has been limited to a standard EDM machine. The work done with micro-EDM is still growing. The University of Jadavpur completed a comparative study with use of a micro-EDM machine and its effects on a titanium work-piece. Yet, the study was not concentrated on the micro-EDM system (Mitra et al., 2009). The study was done with and without the use of a dielectric fluid (EDM oil). The EDM process without dielectric is known as dry-EDM, where there is a tiny atmospheric air gap between the tool electrode and the actual workpiece. What was discovered was there were significant changes in the overall removal rate of the material when a dielectric fluid is present rather than not. This is due to the bubble that is formed within the dielectric fluid and its overall expansion that is restricted by the viscosity of the liquid. This gives the impression that the bubble and dielectric liquid has a lot to do with the material removal rate.

Spark Gap

There are many parameters, variances, and contributing factors to finding the best way to deliver quality results in EDM. A study based on the gap that is between the tool electrode and the workpiece was performed. Although the experimental set up was located in the wire EDM system, it was concluded that the pulse duration from the generator was one of the main factors that affects the spark gap and the overall surface finish (Basil, Paul & Isse, 2013). A direct correlation was determined through the formula.

$$\text{Spark gap} = \frac{(\text{kerf width} - \text{tool diameter})}{2}$$

The results deemed that the gap increased directly with an increase in pulse time. The pulse duration along with other factors such as interaction of the dielectric pressure and the interaction of the pulse energy level influences the spark gap. The spark gap directly influences the dimensional accuracy of the finished part. The settings of these factors need to be monitored carefully to prevent wire breakage in WEDM and can also have an effect on the time it takes to machine a work-piece.

Tool Shaping

The overall tool wear was attributed to the discharge occurring throughout the EDM process. However, there is yet another change that occurs. That is the shape of the tool piece. Ekmekei and Sayer (2013) pointed out that the original shape of the tool piece, specifically the tip, is a blunted geometry, which throughout the EDM process changes into more of a concave shape. This phenomenon was noted in the machining of micro-holes. The study was conducted to figure out why this was occurring and to what extent it affects the performance in the complete machining process. The results concluded that the debris particles that were being machined had a large role in the EDM process. The pulse energy being either high or low gave two distinct outcomes. For the lower pulse energy supplied, it was found that the piled-together particles vaporize without any effect to the tool tip, resulting in a cone shape. The opposing higher pulse accumulated in a slight concaved form. The two results gave insights into how the pulse energy and the manipulation of the debris within the dielectric fluid can be used as an aid when it comes to the TWR of the tool electrode.

Methodology

This study was conducted in three parts. The first part was to use the micro-EDM set-up to machine a series of micro features using a brass work-piece and tungsten carbide electrode tool. This was done utilizing a very specific set of parameters, which are listed below:

Table 1

Experimental Conditions for Micro-EDM of Brass and Titanium Workpieces

Voltage	60V
Capacitance	1000pF
Tool rotational speed	3500 rpm
Tool piece	Tungsten Carbide (Diameter = 300 micron)
Dielectric Oil	EDM Oil
Work piece(s)	Brass and Titanium

Machine Pattern(s)

- 5 x 5 micro-holes (through)
- Letter H (blind)
- 3 blind slots
- 3 through slots

In the second part of the study, the machining process was repeated with the same set of parameters utilizing a titanium workpiece. The two sets of data were compared in order to evaluate the micro-EDM machinability of titanium alloy compared to easy to machine brass materials. It is vital to the quality features of micro-parts to have dimensional accuracy and consistent surface roughness. Also, due to grain orientation of different metals, the repeatability of processing results could vary. Thus, there is a need for comparing the machinability of two materials at the same sets of machining parameters.

After the workpiece was machined, a series of analysis were run on the micro-features to measure their dimensional accuracy, surface quality, and elemental composition. There was a comparison of the dimensional accuracy, elemental composition, and surface integrity of each work piece. The applications that this can be used to influence are fuel injectors or mold manufacturing for microinjection molding. The third and final part of the study was to utilize a Scanning Electron Microscope (SEM) to gather photos of the machined areas and patterns. The SEM uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens. (Magnifications range from 20X to approximately 30,000X, and spatial resolution of 50 to 100 nm.) The SEM not only creates the pictures of the holes and slots, but also can scan the work pieces for their composition. The energy dispersve X-ray (EDX) analysis and spectrum were supplied to measure the elements that were associated with the sample. The charts generated were used to compare both similarities and differences in the components between work pieces. The chemical composition and the properties of the workpiece and electrode materials are listed in Appendix A.

In order to perform the machining on the brass and titanium workpiece, a desktop micro-EDM machine was used. The model of the machine is SmallTech ED009. Figure 1 shows the photograph of the micro-EDM setup. The major components of the micro-EDM setup are the machine tool itself, the pulse generator, the CCD camera associated with the monitor and the microscope for in-situ analysis. A more detailed image of the micro-EDM machine tool is shown in Figure 2. The Figure 2 shows different parts and components of the micro-EDM machine tool.

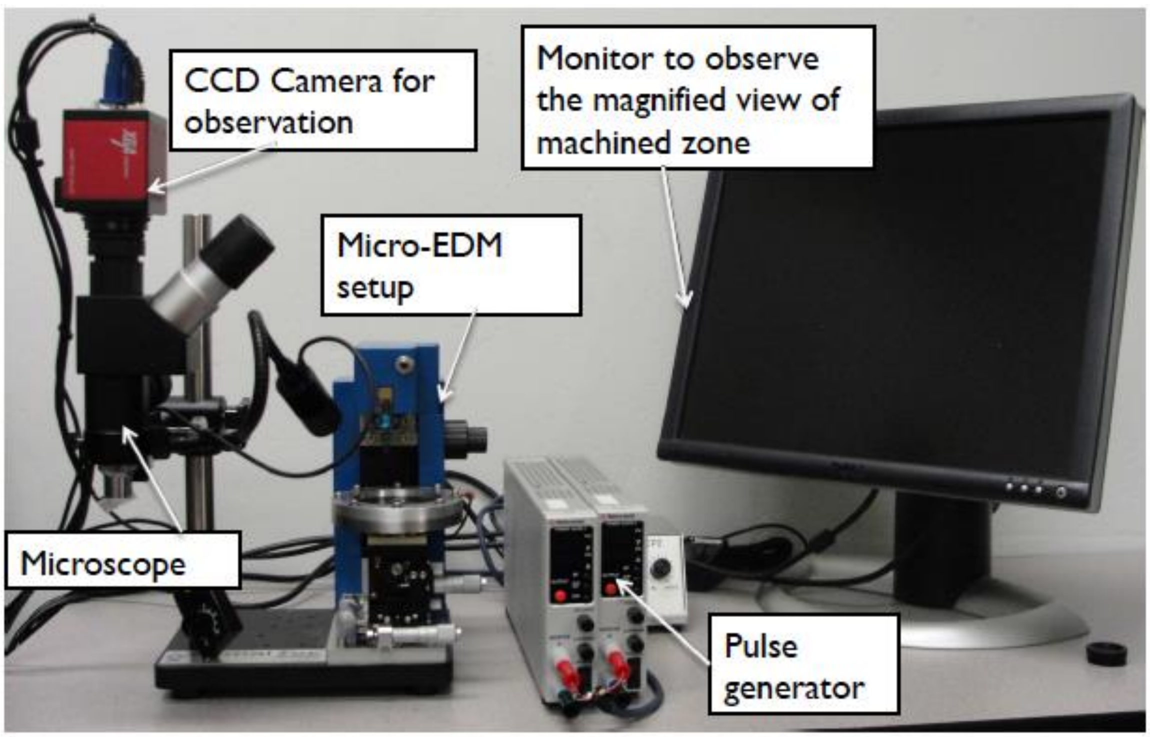

Figure 1. Micro EDM Set-up

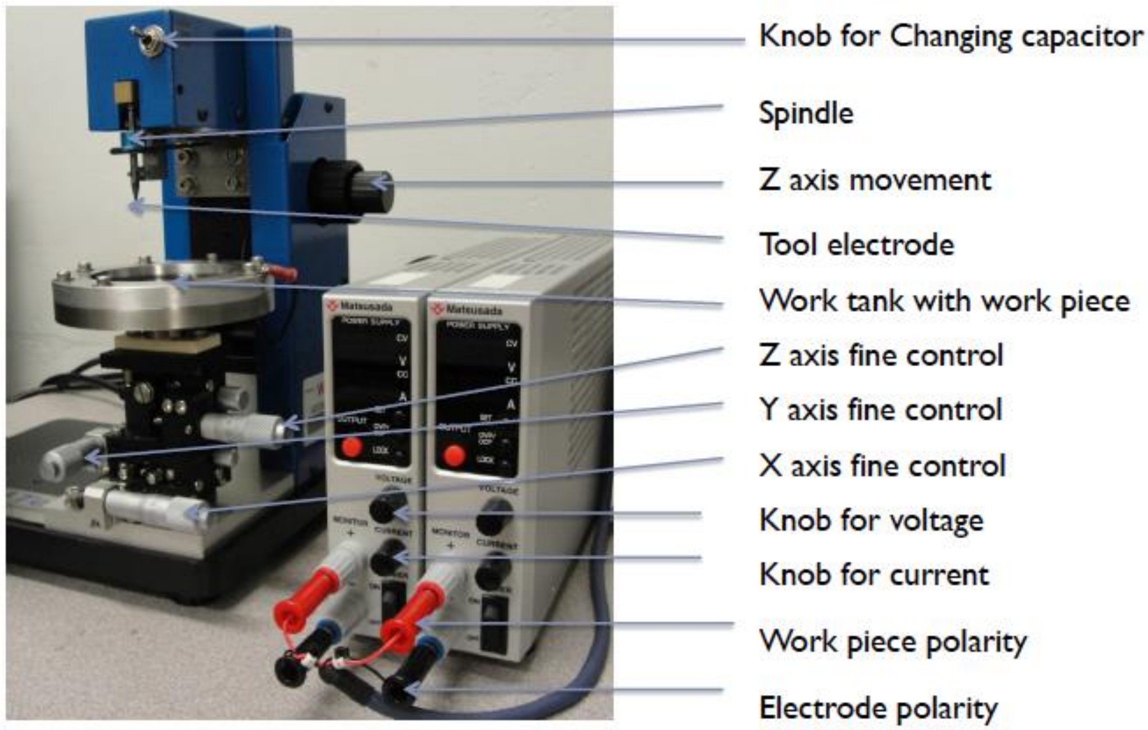

Figure 2. Detailed image of the Micro EDM machine tool

Results and Discussions

Micro-electrical discharge machining (micro-EDM) is a process of removing electrically conductive materials by rapid, repetitive spark discharges from pulse generator with dielectric flowing between tool and work piece. The procedure that was explained in the methodology was followed for both of the work pieces. The machining parameters also were kept the same between them as well. This was done to gain a more clear perspective of how much variation is seen and the difference involving the two alloys. There were many distinct changes between the alloys, not only in the machining process, but also in the final result of the EDM process.

Single Through Micro-Hole

Figures 3-5 show the SEM images of the brass micro-holes machined using the micro-EDM process. The single through hole from the brass work piece measured within a range of 200-250 um. The holes were very smooth around the edges. This could have been caused by the soft nature of the brass material, which allowed the flushing of the incinerated debris. There is an obvious taper from the initial point of contact between the electric sparks to the work piece. This is also a sign of the electrode tool wear as seen from Figure 3. Traditional machining technique is based on the material removal using tool material harder than the work material. On the other hand, the electrical discharge machining (EDM) is based on the eroding effect of an electric spark on both the electrode and workpiece used. Electrical discharge machining (EDM) actually is a process of material removal phenomenon using electrical discharges in dielectric. The electrode plays an important role, which affects the material removal rate and the tool wear rate.

The less electrode wear ratio (EWR) will make the machining performance better. It can be seen from Figures 4 and 5 that, compared to the entrance side, the micro-hole is very smooth at the exit side. This is due to the sparks that are generated at the contact points of the tool and electrode and also due to the tendency of the tool being tapered during machining.

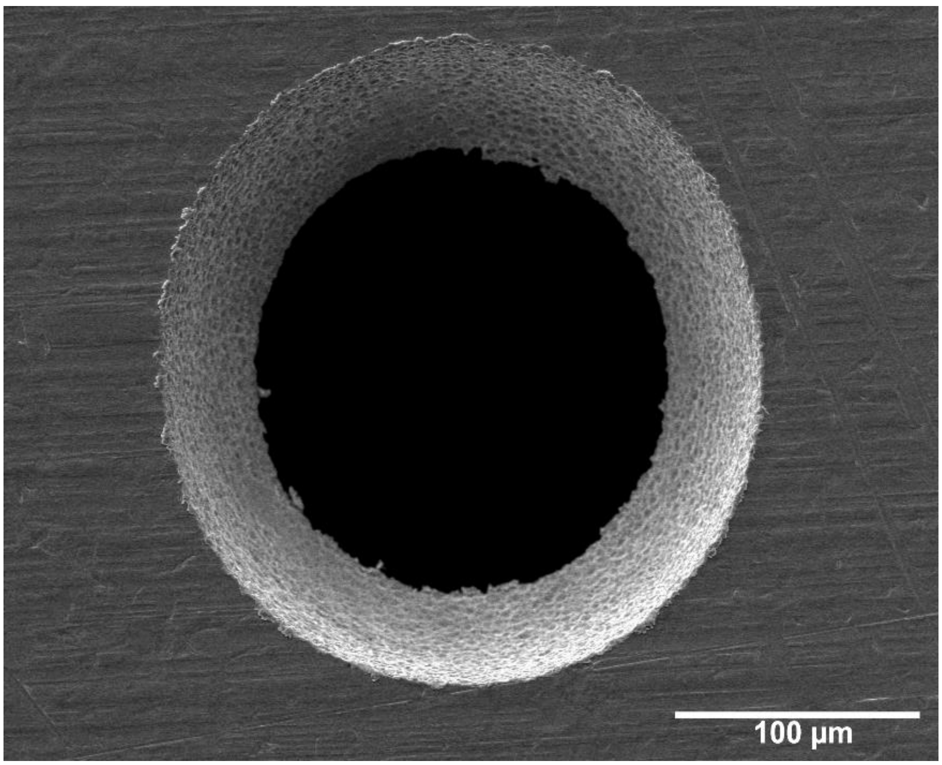

Figure 3. Single Through Hole Entrance (Brass)

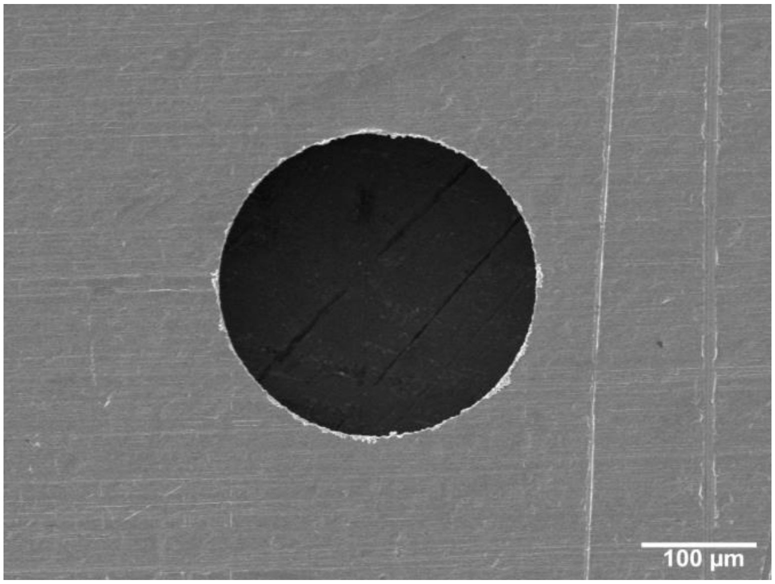

Figure 4. Single Through Exit Hole (Brass)

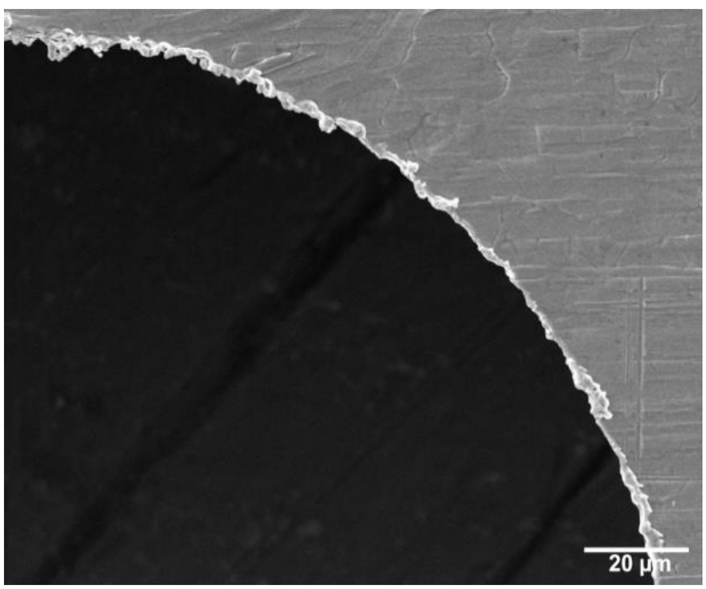

Figure 5. Single Through Exit Edge

Figures 6-8 show the SEM images of the through hole machined on the titanium alloy (Ti-6Al-4V). The compared single through hole in the titanium work piece measured within the same 200- 250 um range. Due to the hardness associated to titanium, the level of debris attached to the hole was higher. This material change under the same parameters also led to a huge decrease in the overall taper associated with the machining. The smooth edges were not found to be present as the brass counter piece. When looking at the edge of each hole (from both brass and titanium) one can clearly see the visible result of re-solidification process and the debris particles on both entrance and exit sides. The exit side from the titanium work piece is very rough compared to that of the brass workpiece with the exit hole being relatively the same size as the entrance side. The opposite brass exit side finds little to no debris and a smooth surface, with the hole measuring five percent less than the entrance hole. This shows the significant taper involved.

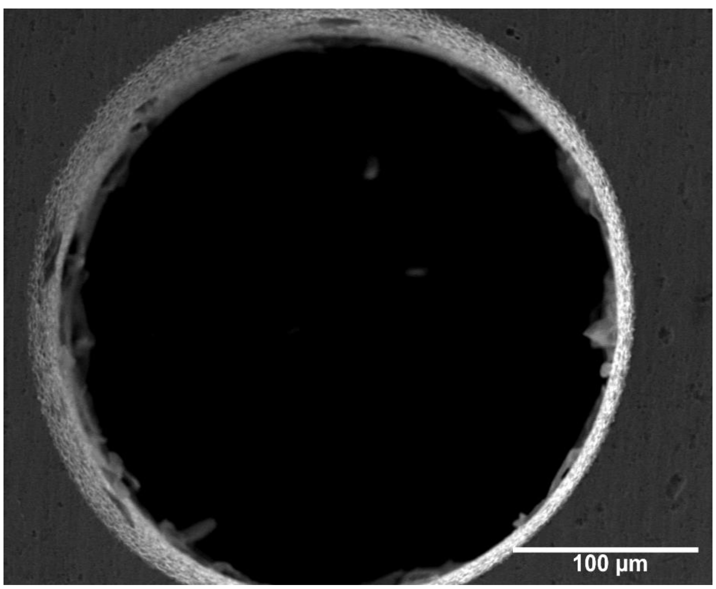

Figure 6. Single Through Hole Entrance (Titanium)

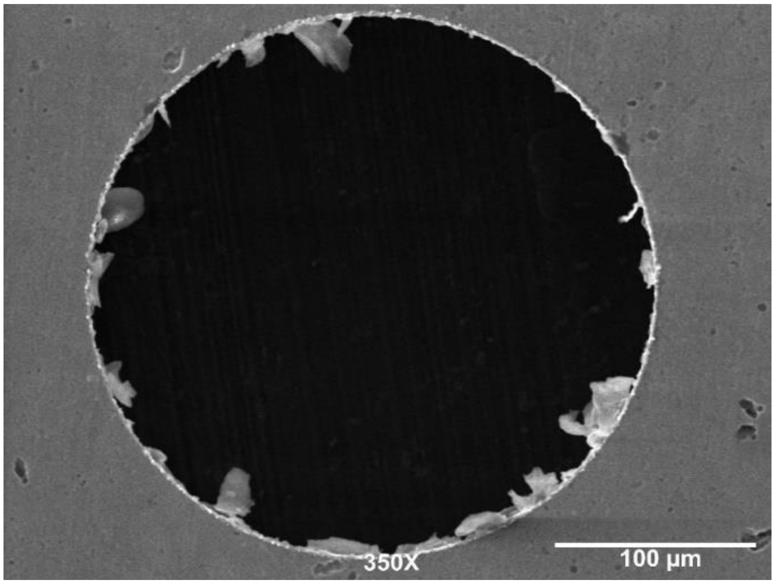

Figure 7. Single Through Exit Hole (Titanium)

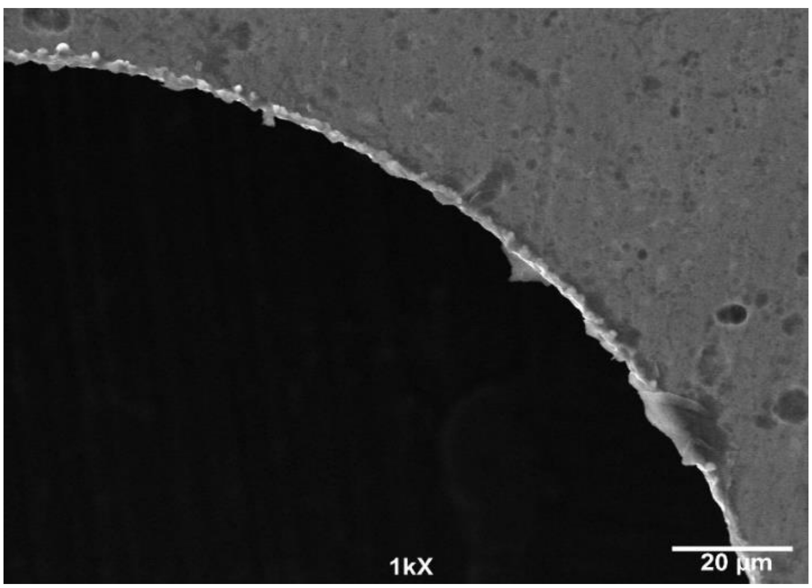

Figure 8. Single Through Exit Edge (Titanium)

Single Blind Micro-Hole

The single blind holes from the brass and the titanium work pieces contain different surface finishes at their edges and centers. These variations occur from the changes in the concentration of the discharge sparks. Usually the sparking concentration or frequency is higher at the center of the holes compared to the edges. This is due to the fact that during the machining, the tool electrode becomes hemispherical or tapered with the center being closer to the workpiece surface. Figures 9 and 10 show the surface topography and the crater arrangement of the blind hole machined on the brass workpiece. Figures 11 and 12 show the same for titanium workpiece. The surface on the brass followed the pattern that was set up in the through holes in regards that it was free from debris with a relatively smooth surface. Upon closer magnification, the surface is compiled of a series of small craters measuring about 5 um per crater. The titanium blind hole is full of debris and areas of irregular machining, as seen from Figure 10. The same overlapping craters exist, but about half the size of the brass work piece, with the craters measuring only 2-2.5 um each.

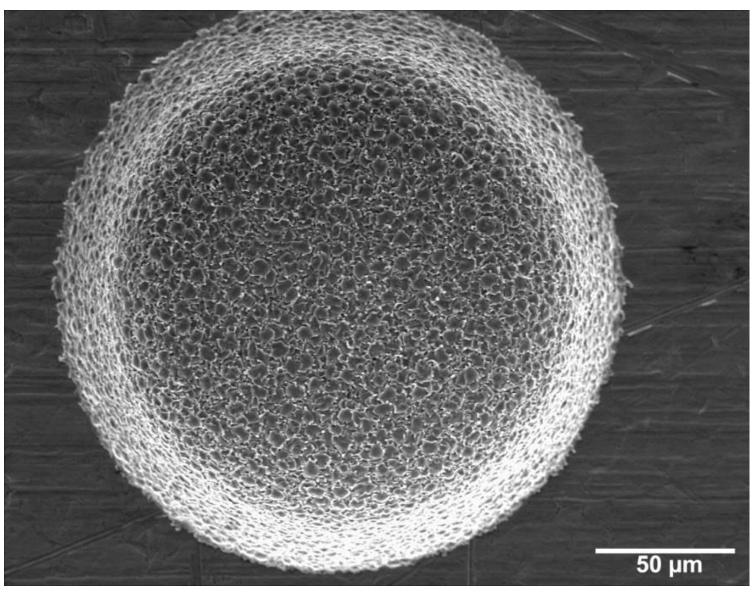

Figure 9. Single Blind Hole (Brass)

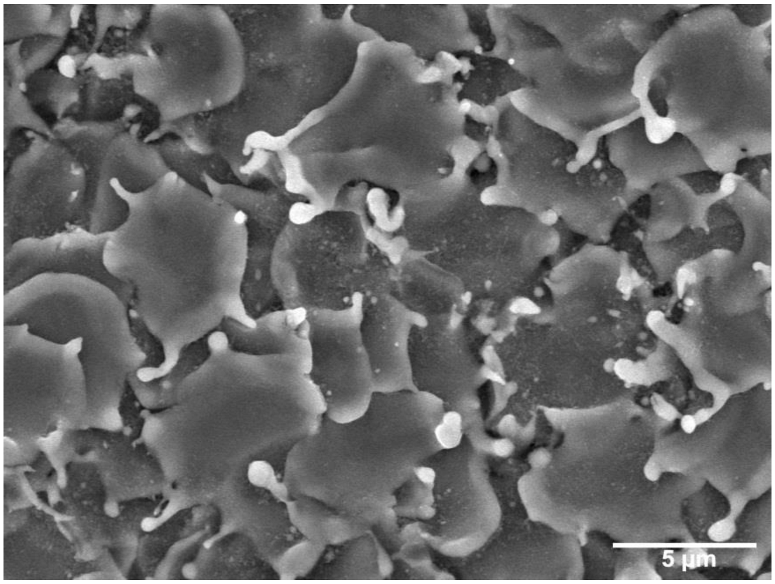

Figure 10. Blind Hole Craters (Brass)

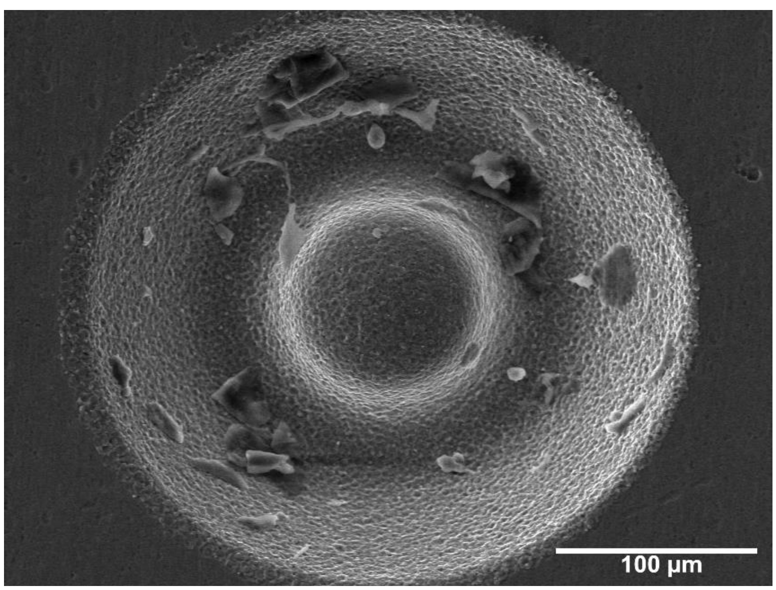

Figure 11. Single Blind Hole (Titanium)

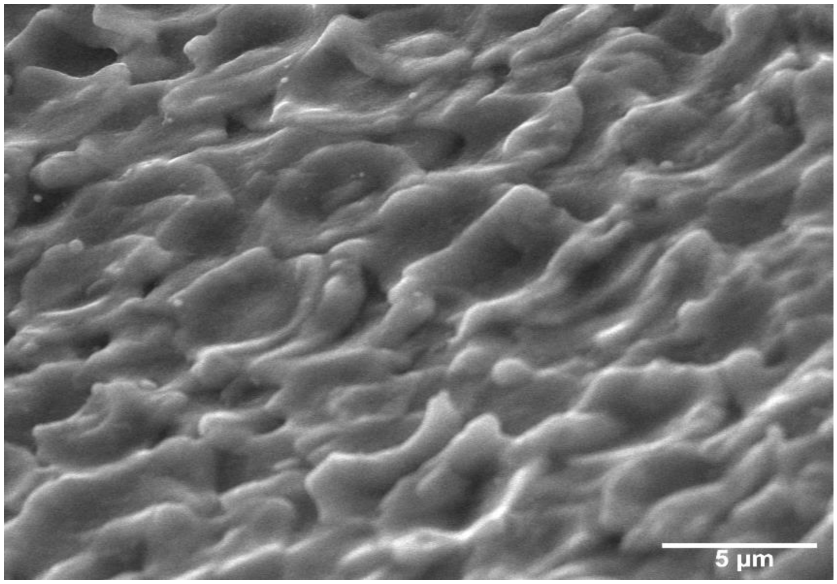

Figure 12. Blind Hole Craters (Titanium)

Energy Dispersive X-ray (EDX) Analysis

One of the major shortcomings of the EDM and micro-EDM process is surface modification after the machining process (Ndaliman et al., 2011). As EDM is the electro-thermal process of removing materials, melting and evaporation take place during the removal the materials. Therefore, there is a possibility of changing chemical composition of the materials as well as migration of new materials from the environment. Therefore, EDX analysis was done in this study to investigate the changes in chemical composition of both brass and titanium workpiece materials.

Figure 13 shows the EDX analysis of the brass workpiece from the two different regions. Point 1 denotes the region without machining and point 2 indicates the edge of the machined hole. The objective of the EDX analysis is to see whether there are any changes at the edge after machining. The spectrum shows the elemental composition breakdown from the machined area and the existing areas not affected directly by the micro-EDM process. Before the machining there was only zinc and copper detected. After the micro-EDM process had taken place, the spectrum showed an influx of oxygen and carbon in the machined areas. The carbon was introduced from the decomposition of the hydrocarbon dielectric oil during machining. The source of the oxygen was from the oxidation of the molten debris around the edge.

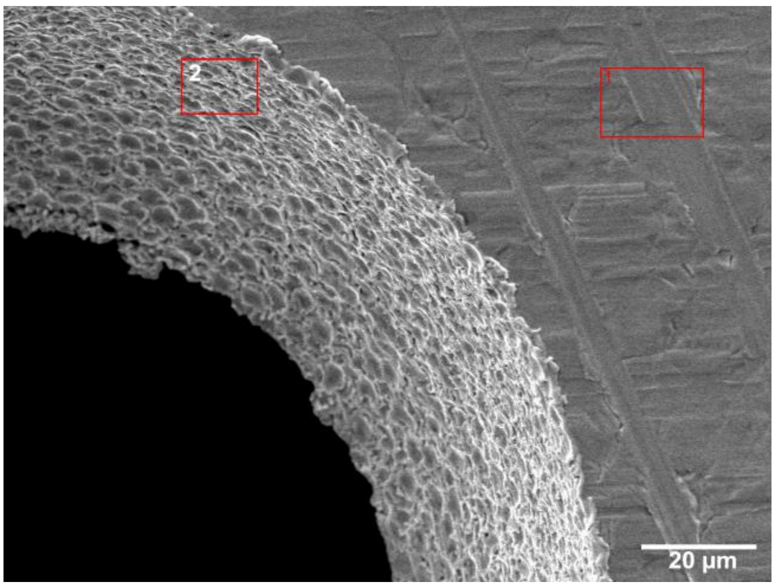

Fig 13(a)

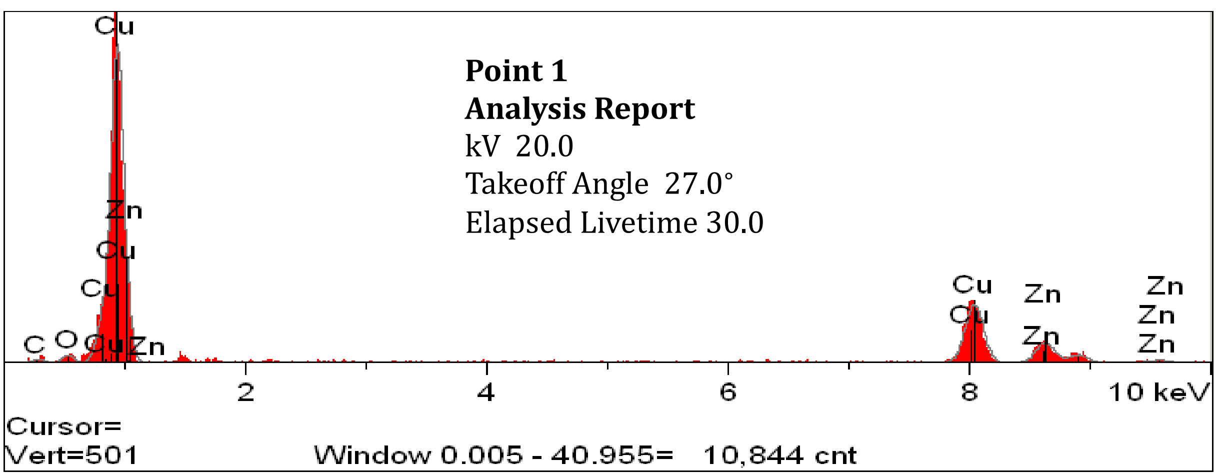

Fig 13(b)

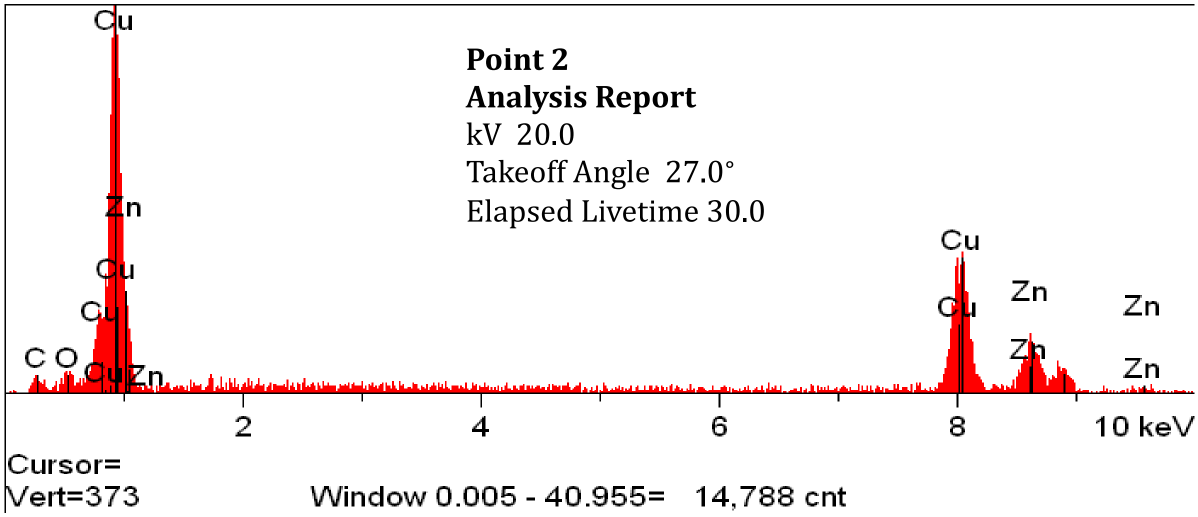

Fig 13 (c)

Figure 13. EDX spectrum analysis of brass before and after machining; (a) SEM image showing point 1 (without machining) and point 2 edge from machined region, (b) spectrum analysis of point 1 and (c) spectrum analysis of point 2

Figure 14 shows the spectrum analysis of the surface of the titanium alloy (Ti-6Al-4V) from the two regions: unmachined and machined by micro-EDM. One obvious difference that can be observed from the SEM images is that the machined hole on the titanium surface includes more resolidified materials around the edge. The resolidified materials could come from either the electrode material or workpiece material. The SEM image of the titanium work piece shows the obvious difference in the taper and the edge width compared to the brass. However, there were not significant differences in the spectrum analysis before and after machining. This finding also indicates that the debris particles that are connected to the micro-hole edge are the craters that are removed from the same workpiece material during the micro-EDM process. This findings also supports the strong alloying tendency of the titanium, which makes it difficult to machine. There may be an introduction of carbon and oxygen from the micro-EDM process due to oxidation and decomposition of the dielectric oil. However, the percentage of oxygen and carbon was not as significant as the brass workpiece as shown in Figure 13.

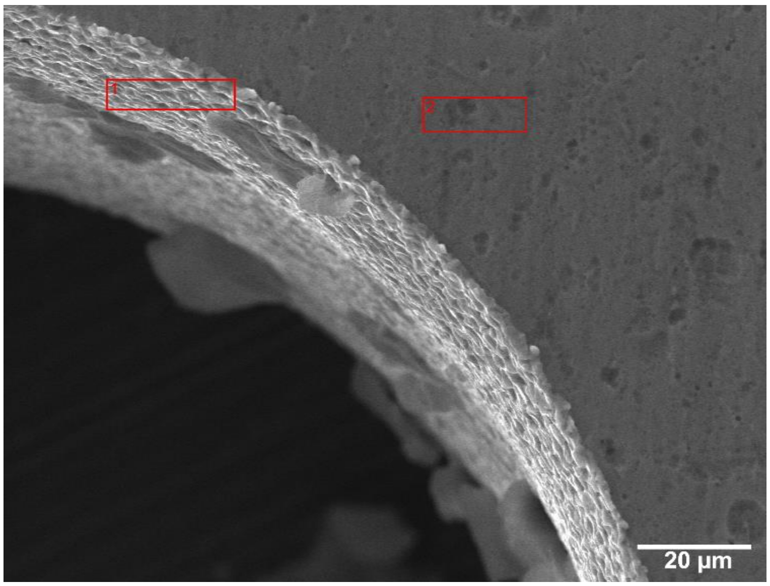

Fig 14(a)

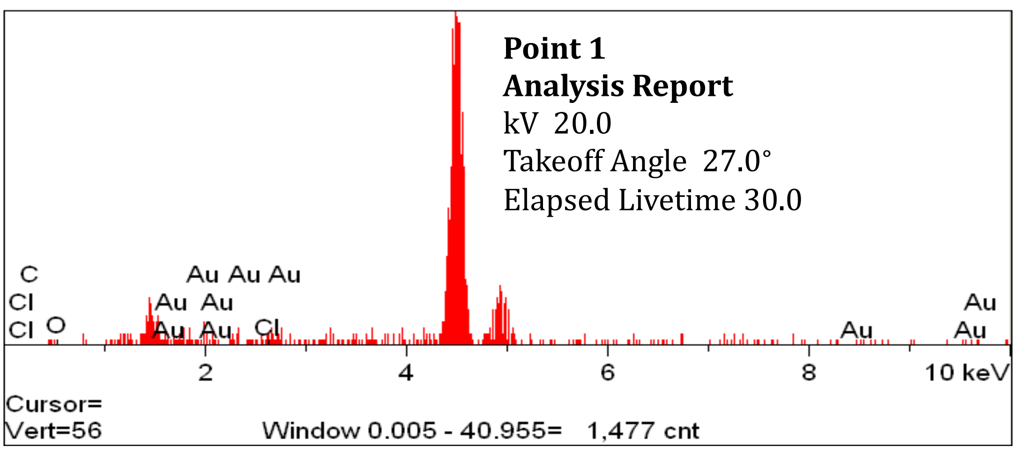

Fig 14 (b)

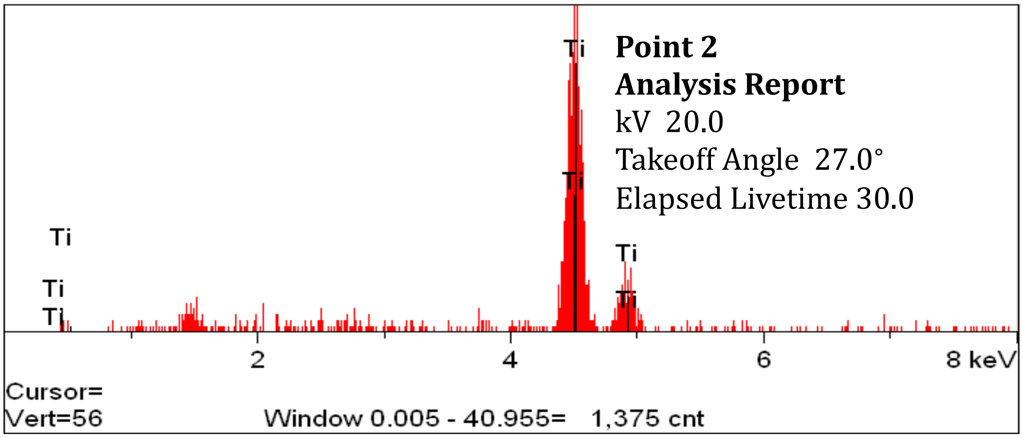

Fig 14 (c)

Figure 14. EDX spectrum analysis of Ti-6Al-4V before and after machining; (a) SEM image showing point 1 (without machining) and point 2 edge from machined region, (b) spectrum analysis of point 1 and (c) spectrum analysis of point 2

Arrays of Micro-Holes

One of the important applications of titanium alloy is that it is being used extensively in aerospace engine parts, such as turbine blades. In order to keep the engine cool, hundreds and thousands of cooling holes are included in the turbine blades and other parts of the engines (Aerospace Techniques, 2014). Therefore, in this study arrays of micro-holes were fabricated in both brass and titanium work pieces and quality of the holes were compared. Due to the limitation of the small desktop machine tool and time constrain, a 5 x 5 arrays of micro-holes were machined. It is possible to fabricate more than 5 x 5 arrays of holes, but the process will be time consuming due to the manual-operating mode of the current micro-EDM setup. In real life applications, a much larger number of holes are required for cooling holes in aerospace engines. The arrays of holes were machined in a 5 x 5 square pattern in both the titanium and brass work pieces. Figures 15 and 16 show the arrays of holes machined in brass and titanium workpieces respectively. Although for both cases, a ϕ 0.3 mm (300 micron) tungsten carbide tool electrode was used, the results were different based on the composition of the work pieces and their properties. The brass is a softer metal and is easily molded and influenced greatly from temperature and other forms of physical manipulation. This, along with the uncontrolled electrode wear (uncontrolled variable), caused the through holes to come about in various sizes and tapers, although the same diameter tool was used for machining all the holes. Almost every individual hole has a different look and dimension. On the other hand, this pattern was not observed in the titanium work piece. The array of holes on the titanium workpiece was much more efficient in its dimensional accuracy. Moreover, all the micro-holes are completely through and of almost same dimensions. Still, the brass array of holes remained cleaner and free from the buildup of debris and particles.

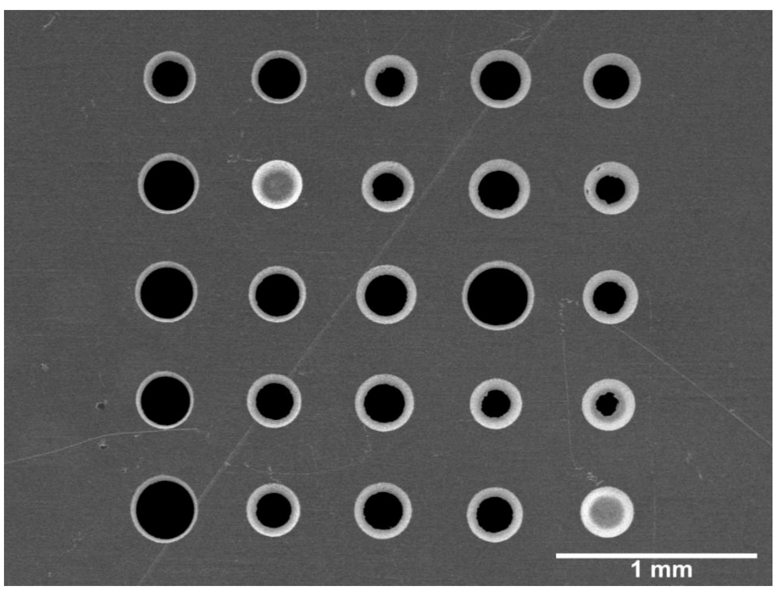

Figure 15. Array of Through Holes (Brass)

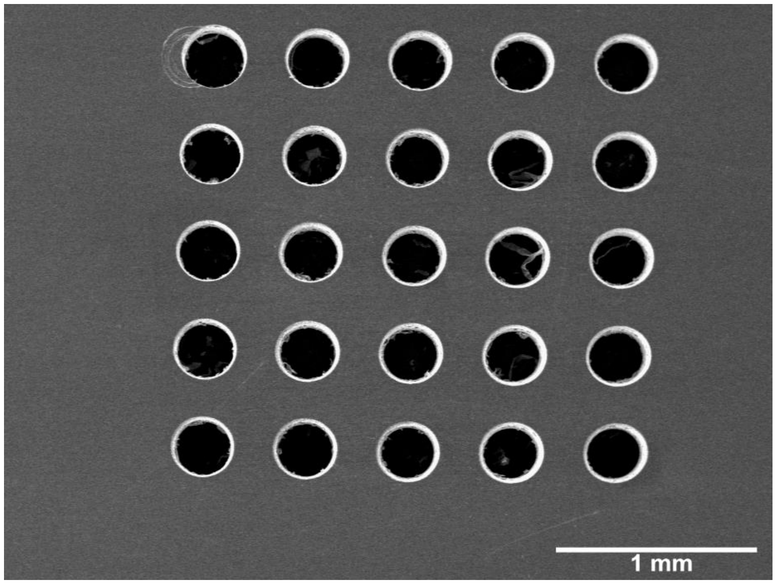

Figure 16. Array of Through Holes (Titanum)

Micro Patterning or Lettering

Micro-EDM can be utilized in various formats. One of those ways is in writing or lettering on a very small scale. This is often used in place of engraving hardened metals with miniature letters and numbers. In this study, the letter “H” was machined in both brass and titanium work pieces, and they were compared for accuracy and overall quality. The brass lettering was uniform and the dimensional accuracy of the holes was very good as shown in Figure 17. Again, the brass’ softer makeup combined with uncontrolled depth resulted in one of the holes being off from the rest. There is a contrast at the center of the blind holes and also at the edges, which have varying widths. Figure 18 shows the machining of same letter “H” on the titanium workpiece. The letter “H” that was machined in the titanium piece contained the same consistency in the dimensional accuracy found in the brass piece. There were varying contrasting sizes of the center circles. The same debris of the titanium-machined areas was once again present. The resolidified debris on the machined surface significantly reduced the quality of the micro-holes produced in titanium workpiece.

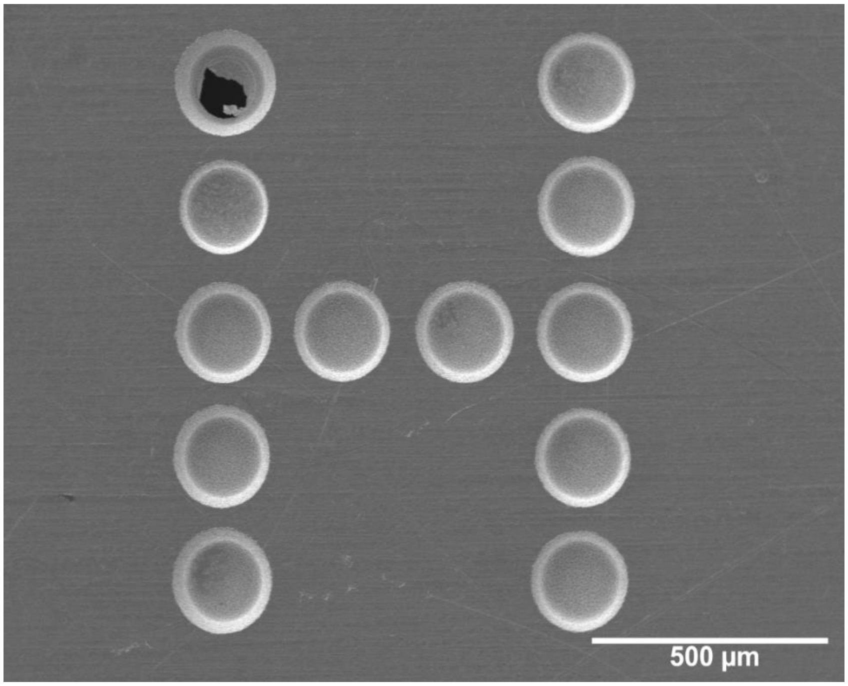

Figure 17. Machining of Letter "H" Using Blind Holes (Brass)

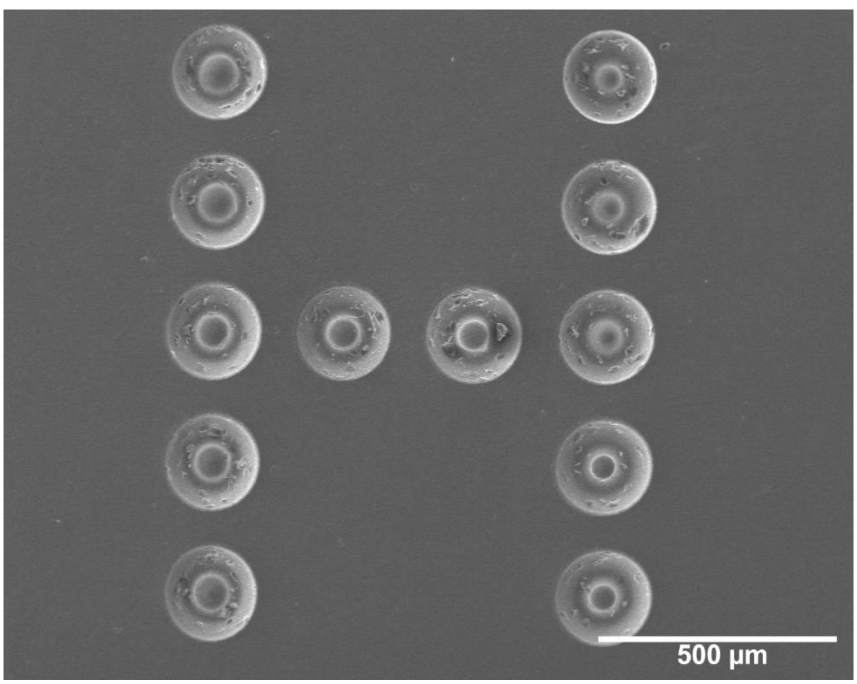

Figure 18. Machining of Letter "H" Using Blind Holes (Titanium)

Machining of Micro Slots

The micro-EDM process that was used for the blind and through micro-holes is commonly termed as die-sinking micro-EDM. All the previously mentioned micro-features were machined using the die-sinking micro-EDM process. In the following section, another variety of micro-EDM (milling micro-EDM) was used to machine blind and through micro slots. The major difference between the die-sinking and milling micro-EDM is that in milling micro-EDM the tool has linear movement in addition to rotational movement, whereas in die-sinking the tool is either stationary or only has rotational movement. In the following sections, machining of blind and through micro slots on brass and titanium work pieces will be presented.

Micro-slots can be used as channels for drug delivery or cooling ventilation (Divera, Atkinsonb, Helmlc, & Lib, 2004). Figure 19 shows the machining of three through micro slots on brass. The magnified view from the edge of a single micro slot is presented in Figure 20. Similarly, the images of machined slots on titanium and a single magnified slot are shown in Figures 21 and 22, respectively. It can be seen that the edges of the through slots differ between materials. The major difference was observed in the shape of the micro slots. It can be seen from Figures 21 and 22 that all three slots fabricated on titanium workpiece are tapered from starting to end point. On the other hand, the slots fabricated in the brass workpiece are of the same dimension at the starting and end points. The taperness associated with the micro slots in the titanium workpiece is due to the significant electrode wear. As the electrode proceeds from the starting point to end point during the machining, the corner wear of the electrodes becomes higher, making the slots taper at the end. The reasons for higher electrode wear during the machining of titanium are the comparatively higher melting point and strength of the titanium. Comparing slots on both work pieces, the brass slots were found to be smoother than those of the titanium. In addition, a visual difference comes to the ending shape of the slots in the titanium work piece. Where the slots remain uniformed and consistent in the width for brass, the titanium slot has a very obvious taper towards the end of the slot. The magnified SEM images of the slots, as shown in Figures 19 and 21, also indicates the differences in the dimensional accuracy and shapes of the slots machined in brass and titanium work pieces. However, there are similarities as well. The similarities that they share were the ends of the slots, where both materials produce clear edges. However, the micro slots fabricated in Ti-6Al-4V have more debris attached to the edge of slots. Similar findings have been discussed in case of micro-holes earlier in this chapter.

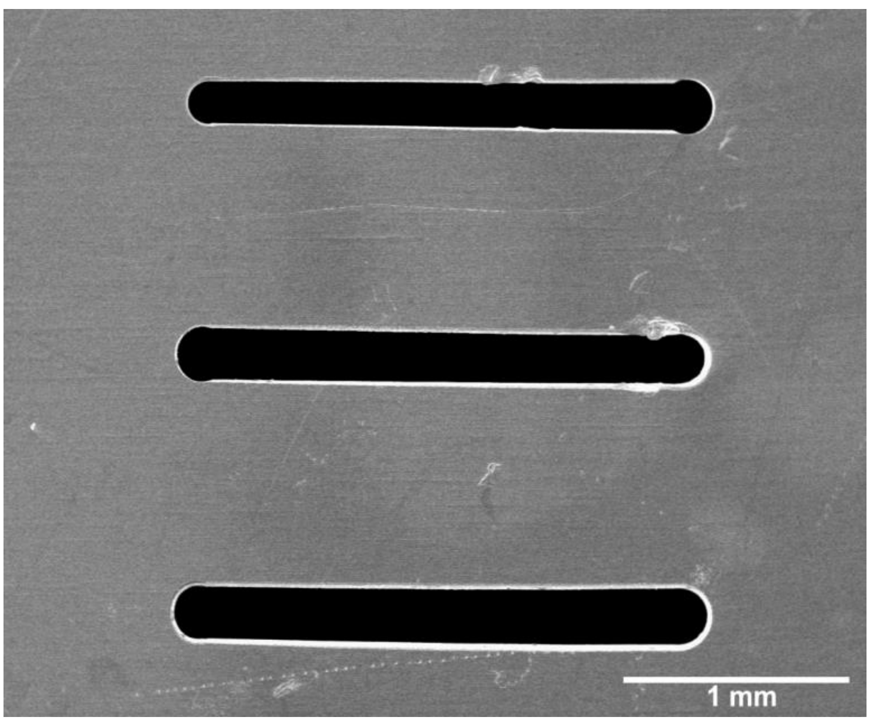

Figure 19. Through Slots (Brass)

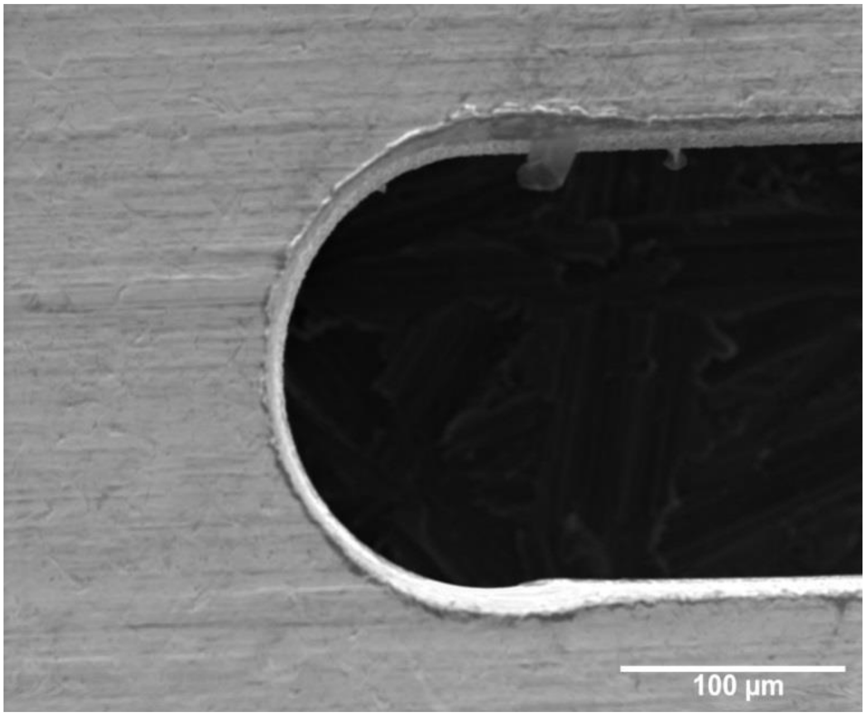

Figure 20. Through Slot Edge (Brass)

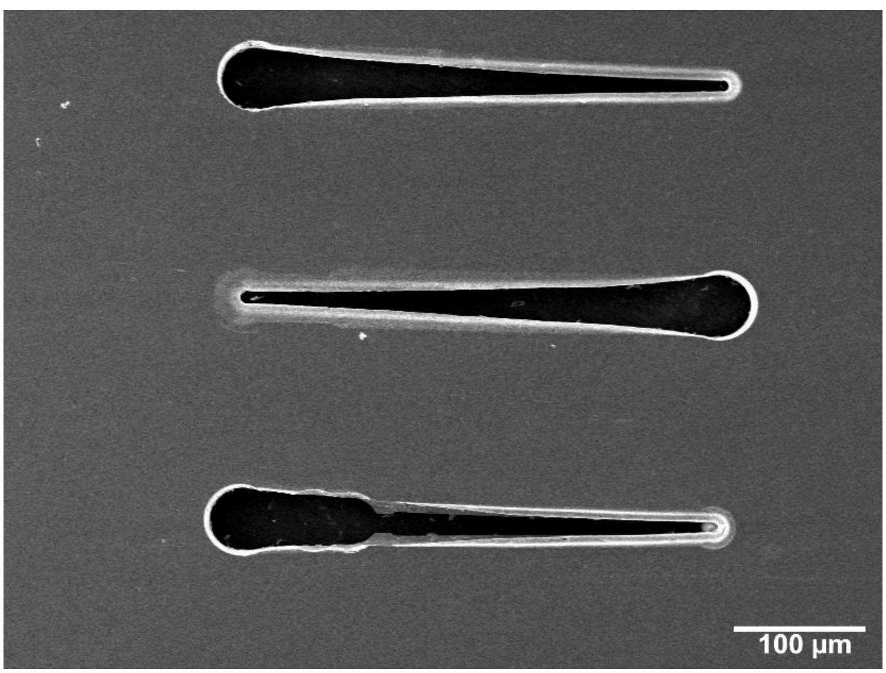

Figure 21. Through Slots (Titanium)

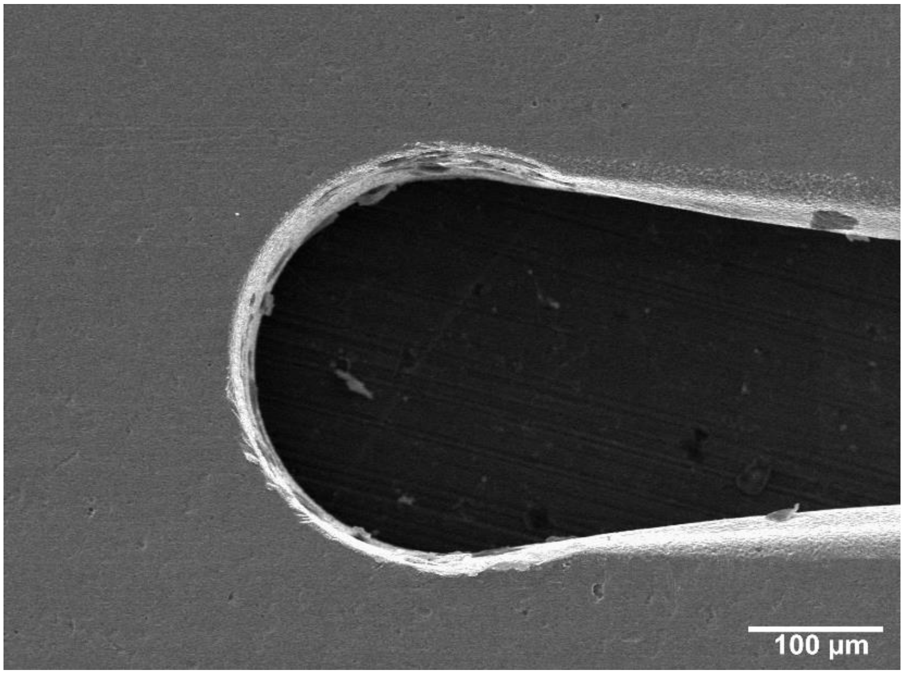

Figure 22. Through Slot Edge (Titanium)

Investigation was carried out to machine blind micro slots on the brass and titanium work pieces. Interestingly, the same results of taperness at the end of the micro slots in titanium workpiece were observed for blind slots. Figures 23 and 24 shows the SEM images of the blind micro slots machined on the brass workpiece. The micro slots of same dimensions machined on titanium workpiece is shown on Figures 25 and 26. The blind slots on the brass workpiece are of uniform dimension and shape with no significant resolidified debris on the surface. The depths of slots were hemispherical due to the corner wear of the electrode tool as can be seen from Figure 23. Similar findings of hemispherical shape were observed in blind slots on titanium workpiece. The brass slot contains a stepped layout around the edge, which is a sign of a different tool diameter formed by in-situ-tool fabrication. The blind slots in the titanium work piece are covered with debris, which was found to be common in all the micro features machined on titanium workpiece. Taper is evident again from the tool wear associated with the hardness of the titanium alloy. There was an obvious and dramatic difference in the machined areas due to the change in work pieces (Brass to Titanium). Tool electrode wear was found to be an important factor of concern resulting in unpredictable machining depth of micro slots.

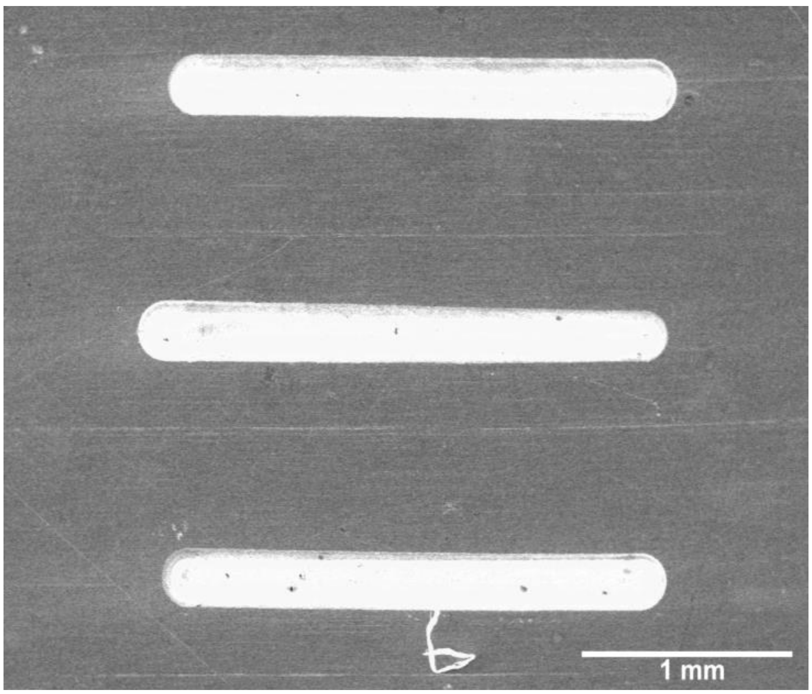

Figure 23. Blind Slots (Brass)

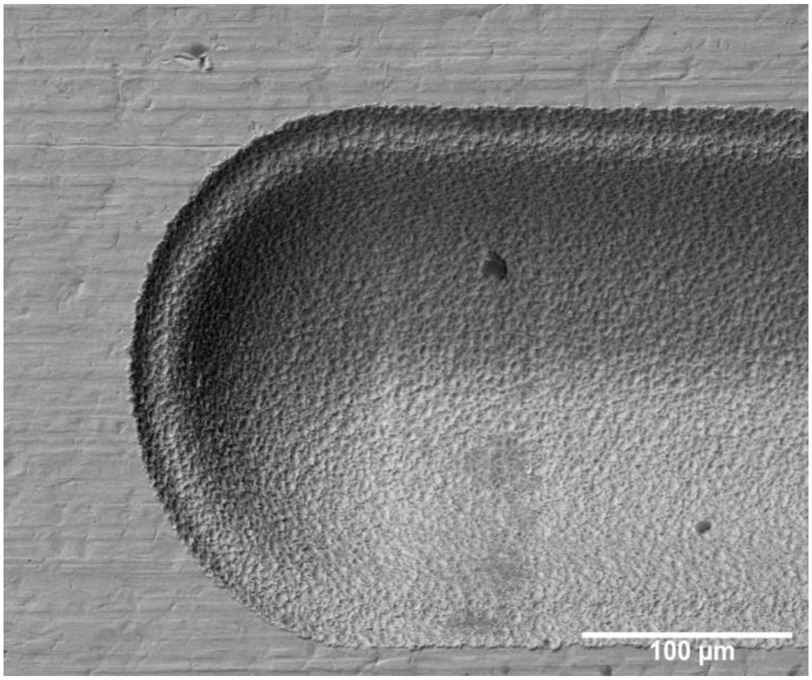

Figure 24. Blind Slot Edge (Brass)

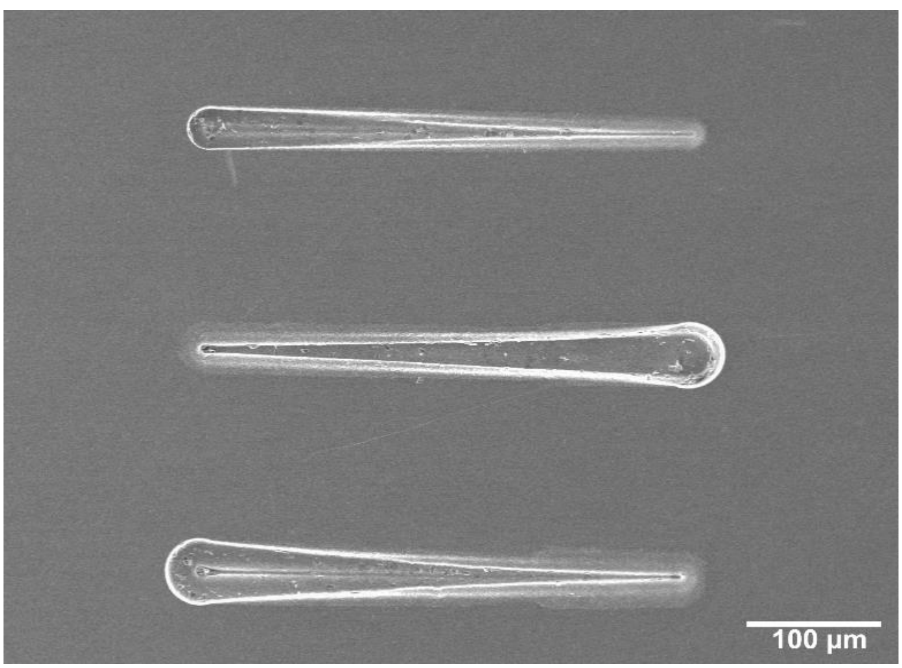

Figure 25. Blind Slots (Titanium)

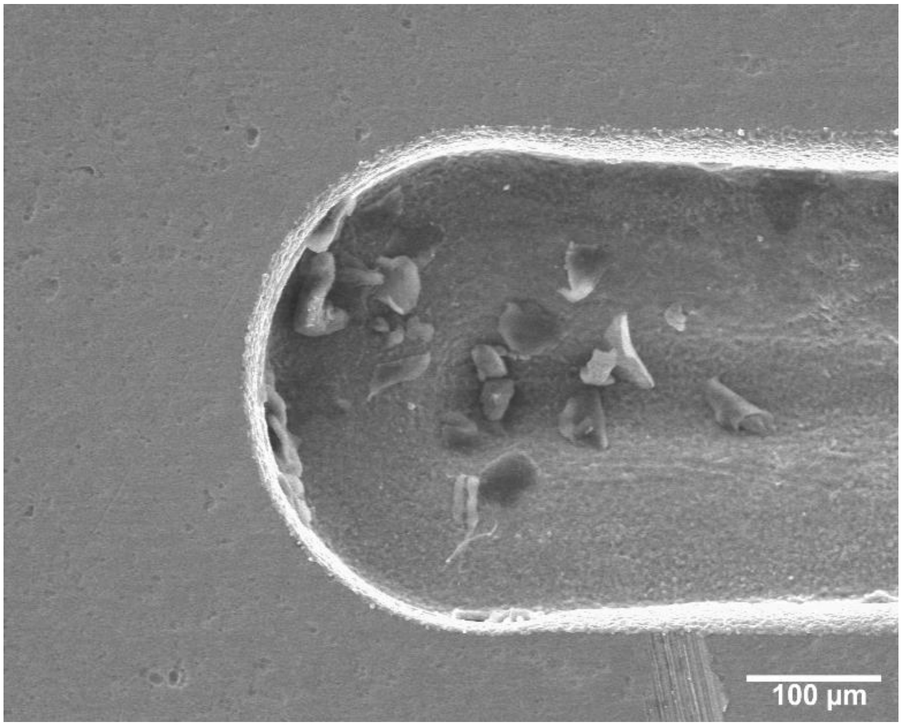

Figure 26. Blind Slot Edge (Titanium)

Conclusion

The purpose of this study was to use the micro-EDM process to investigate its ability to perform a series of holes, slots, and patterns on difficult-to-cut titanium alloy (Ti-6Al-4V), utilizing the list of hypothesis stated in the beginning of this study. In order to better understand the machinability of titanium alloy, the machining performance was compared with that of an easy-to-machine material brass. The machining performances of the two materials were evaluated based on the quality of the micro-features machined. The secondary objective was to observe surface finish, quality, and elemental composition changes of the various shapes micro features machined on two materials.

The study concluded the estimated hypothesis that micro-EDM is an acceptable form of machining titanium alloys (H1). The process and parameters that were used were effective in machining both soft metals as well as metals that can withstand higher temperatures like Ti-6Al-4V. The titanium set of blind hole and blind slots contained a larger amount of debris build up than the brass material and correctly supported the hypothesis (H3, H5). The same was true for the through holes and slots for the titanium alloy, as it allowed a greater amount of build up from the debris particles left by the EDM process. This again, was attributed to the hardness of the titanium alloy and its properties (H2, H4).

Brass has a much lower melting point than titanium and the grain structure consists of much larger grains. Using the same spark energy, when the brass work pieces are being machined, more material was melted and therefore larger pieces of material float in the gap as debris than for titanium. When using a rod electrode to erode a hole in soft materials like brass, after reaching a certain depth, the flushing conditions deteriorate rapidly. It was found that the larger the debris the more difficult it would be to be flush them out of the sparking area. This debris causes sparking on the side of the electrode, breaking the debris into smaller pieces and finally flushing them out of the sparking area. This also explains the change in electrode wear and taperness of the holes in the brass workpiece. The holes that were machined though the depth of the workpieces and slots in the brass were smoother compared to the titanium counterpart. This was attributed to the ability of the dielectric fluid to flush away the debris of the softer materials. The holes and slots of the titanium work piece ended with rough edges and were all riddled with debris.

The EDX analysis for both brass and titanium work pieces before and after machining confirmed very little changes or surface modifications after micro-EDM. There was some addition of carbon and oxygen to the machined surface after the micro-EDM process. The carbon was from the decomposition of the dielectric oil and the presence of oxygen was due to the oxidation of molten metal at higher temperature.

The more significant differences were observed during the machining of micro slots. For both thorough and blind micro slots, the shape becomes tapered at the end of the slots in titanium work piece, whereas no significant change in the shape was observed in the brass work piece. This is due to much higher tool electrode wear during machining of titanium alloy due its higher melting point and strength.

For all types of micro features, there is more debris attached/resolidified to the machined surface during micro-EDM of the titanium alloy. This is due to the strong alloying tendency of titanium alloy at higher temperature, which also makes it difficult to machine using conventional machining processes. In addition, the debris particles of heavier metal are found to be difficult to flush away from the machined zone compared to light metals using low pressured flushing.

Consequently, this research endorses the continued use of micro-EDM in manufacturing parts and components made of titanium alloys. Micro-EDM is a growing form of manufacturing and will continue to expand in various production fields. In future production of materials using micro-EDM, this research would suggest the introduction of an automated set up. At this point, micro-EDM is a manual process, which can be very accurate in its dimensional accuracy and create quality patterns or holes, but is also very time consuming. An automated system can also take out the possibility of human error as well as making the process faster. Automation can always be accounted for as a factor when present in any form of production.

Recommendations for Future Work

With the completion of this thesis, machining characteristics and machining behavior of micro-EDM can be estimated and predicted easily. Even with titanium being such a valued resource in aerospace materials, it does have one major problem. Titanium is very difficult to machine due to its hardness and strength. This is the main reason why the titanium market is such a finite one, which usually has very specific and unique uses. EDM and micro-EDM are the current solutions to manipulate and machine titanium and other aerospace materials.

Future studies should focus on solving the issues reported in this thesis. The major problems associated with the micro-EDM of titanium alloy are higher tool wear, taper of the micro slots during milling micro-EDM, and resolidification or attachment of debris particles on the machined surface. In order to solve the issues, the assistance of external sources can be investigated for machining of titanium alloys. Some examples of the assisted micro-EDM process that are found to be successful in literature are vibration-assisted micro-EDM, abrasive assisted micro-EDM, and powder mixed micro-EDM (Jahan, 2013).

Appendix A: Properties of Electrode and Workpiece Materials

Table A1.

Composition and properties of Tungsten Carbide

Property	Min.Value(S.I)	Max.Value(S.I)	Units(S.I)	Max.Value(Imp)	Min.Value(Imp)	Units(Imp)
Atomic Value	.0062	.0064	Mg	378.347	390.552	kmol
Density	12.25	15.88	Mj	952.027	991.357	lb/ft.
Energy Content	150	200	GPa	16250.8	21667.7	kcal/lb
Bulk Modulus	350	400	MPa	50.7632	58.0151	psi
Compressive Strength	3347	6833	MPa	485.441	991.043	ksi
Ductility	.005	.0074	NULL	.005	.0074	NULL
Eleastic Limit	335	530	MPa	48.5876	76.87	ksi
Fracture Toughness	2	3.8	MPa	1.82009	3.45818	ksi.in
Hardness	1700	36000	MPa	2465.64	5221.36	ksi
Loss Coefficient	5e-005	.0001	NULL	5e-005	.0001	NULL

Table A2.

Chemical composition of Ti-6Al-4V alloy (wt. %)

Ti	89.464
Al	6.08
V	4.02
Fe	0.22
O	0.18
C	0.02
N	0.01
H	0.0053

Table A3.

Material properties of Ti-6Al-4V

Hardness (HV20)	600
Melting point (C)	1660
Ultimate tensile strength (MPa)	832
Yield strength (MPa)	745
Impact-toughness (J)	34
Elastic modulus (GPa)	113

Table A4.

Material properties of brass

Properties	Metric	English	Comments
Tensile Strength	338-469 MPa	49000-68000 psi	Depending on temp.
Bulk Modulus	140 GPa	20300 ksi	Typical for Steel
Elongation	53%	53%	In 457.2 mm
Machinability	100%	100%	
Shear Modulus	37 GPa	2370	
Conductivity	115 W/m-k	798 BTU	
Melting Point	885-900 C	160-1650 F	UNS (free cutting brass)
Density	8.49 g/cc	.307 lb/in	

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