EVALUATION OF ELECTRICAL DISCHARGE MACHINING PARAMETERS ON ENERGY SAVING AND MACHINING CHARACTERISTIC ENHANCEMENT OF BIODEGRADABLE AZ31 MAGNESIUM ALLOY

NORIZWAN BIN JURAIMI

SULTAN IDRIS EDUCATION UNIVERSITY

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ABSTRACT

Magnesium alloys have been widely used in biodegradable applications due to their propensity for corroding within the human body and their initial mechanical properties. However, recent research has shown that the increased rate of magnesium deterioration inside the human body causes structural stability of the implant to be disturbed and lost quickly. Electrical discharge machining (EDM) die sinking is a machining technique used to produce complex forms with high tolerance in magnesium alloy, focusing on the relationship between process parameters and machining effect. The research aims to investigate the effect of EDM process parameters on surface roughness, material removal rate (MRR), and energy consumption to optimize and validate the machining parameter prone to energy saving and the best machining characteristic. The experiments were optimized using a design of experiment approach with a full factorial design and response surface methodology. The relationship models between the controlled design parameters of pulse-on-time, pulse-off-time, and peak current and the responses of material removal rate were validated through confirmation runs, and the average percentage errors between experimental data and predicted values for each response were within the acceptable range (less than or equal to 10%). Pulse-on-time was the prominent factor that affects the material removal rate and surface roughness, while pulse-off-time appeared to be the most influential parameter for energy consumption. Nonetheless, peak current appeared to be insignificant among all factors in this study as it depends on the level of pulse-on-time applied. Higher pulse-on-time caused larger surface roughness. Therefore, surface integrity of the workpiece depends on the level of pulse-on-time applied. The optimum setting parameter combination to achieve optimum response MRR (0.041 g/min), surface roughness (3.191 µm) and energy consumption (0.702 J/g) was high peak current (14.00 A), low pulse-on-time (2.00 µs), and low pulse off time (10.00 µs).

PENILAIAN PARAMETER PEMESINAN PELEPASAN ELEKTRIK PADA PENJIMATAN TENAGA DAN PENINGKATAN CIRI PEMESINAN ALOI MAGNESIUM AZ31 TERBIODEGRADASI

ABSTRAK

Aloi magnesium telah digunakan secara meluas dalam aplikasi biodegradasi kerana kecenderungannya untuk menghakis dalam tubuh manusia dan sifat mekanikal awalnya. Walau bagaimanapun, penyelidikan baru-baru ini menunjukkan bahawa peningkatan kadar kemerosotan magnesium di dalam tubuh manusia menyebabkan kestabilan struktur implan terganggu dan hilang dengan cepat. Pemesinan pelepasan elektrik (EDM) die tenggelam adalah teknik pemesinan yang digunakan untuk menghasilkan bentuk kompleks dengan toleransi tinggi dalam aloi magnesium, yang memberi tumpuan kepada hubungan antara parameter proses dan kesan pemesinan. Penyelidikan ini bertujuan untuk menyiasat kesan parameter proses EDM pada kekasaran permukaan, kadar penyingkiran bahan (MRR), dan penggunaan tenaga untuk mengoptimumkan dan mengesahkan parameter pemesinan yang terdedah kepada penjimatan tenaga dan ciri pemesinan terbaik. Eksperimen dioptimumkan menggunakan reka bentuk pendekatan eksperimen dengan reka bentuk faktorial penuh dan metodologi permukaan tindak balas. Model hubungan antara parameter reka bentuk terkawal denyutan pada masa, masa denyutan, dan arus puncak dan tindak balas kadar penyingkiran bahan telah disahkan melalui larian pengesahan, dan ralat peratusan purata antara data eksperimen dan nilai yang diramalkan untuk setiap tindak balas berada dalam julat yang boleh diterima (kurang daripada atau sama dengan 10%). Pulse-on-time adalah faktor utama yang mempengaruhi kadar penyingkiran bahan dan kekasaran permukaan, sementara waktu denyutan nampaknya menjadi parameter yang paling berpengaruh untuk penggunaan tenaga. Walaupun begitu, arus puncak nampaknya tidak penting di antara semua faktor dalam kajian ini kerana ia bergantung pada tahap denyutan pada masa yang digunakan. Denyutan pada masa yang lebih tinggi menyebabkan kekasaran permukaan yang lebih besar. Oleh itu, integriti permukaan bahan kerja bergantung pada tahap denyutan pada masa yang digunakan. Gabungan parameter tetapan optimum untuk mencapai MRR tindak balas optimum (0.041 g/min), kekasaran permukaan (3.191 μm) dan penggunaan tenaga (0.702 J/g) adalah arus puncak tinggi (14.00 A), denyutan pada masa rendah (2.00 μs), dan masa mati nadi rendah (10.00 μs).

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
DOE	Design of experiment
EDM	Electrical discharge machining
HAZ	Heat affected zone
I_p	Peak current
MRR	Material removal rate
Ra	Arithmetical mean roughness
RL	Recast layer
SV	Servo voltage
T_{off}	Pulse-off-time
T_{on}	Pulse-on-time
WEDM	Wire electro discharge machining

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CHAPTER 1

INTRODUCTION

1.1 Background

The acceptance of an artificial implant by the surrounding tissues and biological system is known as biocompatibility, and it is one of the most important criteria to consider when selecting a metallic implant (Mas-Ayu et al., 2014). At the moment, titanium (Ti) alloys, stainless steel, and cobalt-chromium (CoCr) alloys are the metallic materials that have been approved and are frequently used in structural implants (Table 1.1). Nevertheless, these metallic materials are prone to corrosion while they are in operation because the corrosive solution that is implanted at the site, in addition to the fact that they are frequently subjected to cyclic loading, makes them sensitive to corrosion. The metallic biomaterials that are currently on the market have the potential to release dangerous metal ions or particles through the processes of deterioration or wear. This can cause an overactive inflammatory response, and it can also irritate the structure that is nearby, both of which can contribute to the formation of cancer (Shah A et al., 2017).

According to Table 1.2, the majority of these materials, with the exception of the element magnesium, exhibit mechanical properties that do not match up with those of real bone tissue. The exception to this rule is magnesium, which has mechanical properties that are identical to those of real bone tissue. This mismatch can lead to stress shielding, which can, in turn, contribute to a slowdown in the stimulation of new bone creation and a decrease in the stability of the bones. It is necessary to undergo a surgical operation in order to extract the permanent implant once the tissue has completely recovered. Metallic biomaterials are employed routinely today, and in vivo, they have, for the most part, no discernible effect. These biomaterials not only held fractures together, but they also remained in place as permanent fixtures. The patient will require more morbidity treatment as a result of the numerous surgeries that are required by this permanent implant. As a result, this will have an influence not only on the cost of health care but also on the system as a whole.

Table 1.1

Major metals and alloys for biomedical applications (Chambolle & Poret, 2005) (Hensen, 2008) (Hermawan et al., 2010).

Material	Major Applications
316L Stainless Steel	Orthopaedic fracture plates, dental implants, spinal rods, joint replacement prostheses, stents, and catheters are a few examples of medical devices.
Cobalt-Chromium alloys	Orthopaedic fracture plates, dental implants, spinal rods, heat valves, and joint replacement prostheses

(continue)

Table 1.1 *(continued)*

Titanium, Nitinol, Titanium alloys	Orthopaedic, fracture plates, joint replacement prostheses, stents, ablation catheters, dental implants, dental wires, and cranial, orbital, and maxillofacial reconstruction.

Table 1.2

A comparison of the structural and mechanical properties of natural bone with those of various implant materials (Atrens et al., 2011) (Gonzalez et al., 2013) (Zhou et al., 2010).

Material	Density (g/cm^3)	Toughness ($Mpa(m^{\frac{1}{2}})$)	Modulus (GPa)	Yield Strength (MPa)
Natural bone	1.8-2.1	3-6	3-20	130-180
Ti alloy	4.4-4.5	55-115	110-117	758-1117
Co-Cr alloy	8.3-9.2	-	230	450-1000
Stainless Steel	7.9-8.1	50-100	187-205	170-310
Magnesium	1.74-2.0	15-40	41-45	65-100
Hydroxyapatite	3.1	0.7	73-117	600

In tandem with the development of biomedical technology and tissue engineering, there is a growing demand for biomaterials that may completely remove the risk of harmful effects caused by leaching, wear, and corrosion. The stress shielding effect and surgical intervention are the two key consequences that need to be minimised in metallic implants. This is where the majority of the worries lie. These requirements prompt the research and development of new biomaterials that are biodegradable and the processing of these materials. The biodegradable implants provide the healing tissue with a temporary mechanical support until either complete tissue regeneration or scarring repair has taken place. The most important advantage offered by degradable implants is that, once they have been completely broken down and dissolved in the human body, they do not have an effect that is detrimental to the healing process of the surrounding tissue. As a result, the patient won't need to go through a second operation like they would have otherwise. Biodegradable metals like magnesium offer an advantage over traditional biodegradable implants made of polymer, ceramic, or bioactive glasses for load-bearing applications that call for initial tensile strength and a Young's modulus that is closer to that of bone (Peter & Maurus, 2004). This is because biodegradable metals like magnesium have an initial tensile strength that is closer to that of bone. Metals that are biodegradable, such as magnesium, decompose at a pace that is slower than that of polymers, ceramics, or bioactive glasses.

Metallic materials have been selected because of a number of reasons, including their resistance to corrosion and other properties, and the concept of a biodegradable implant has even gained recognition at this point. In orthopaedic and cardiovascular surgical applications, magnesium is the preferred material to use as a biodegradable metal implant. One of the elements with the potential to be used in biodegradable metal implants in orthopaedic and cardiovascular surgical procedures is magnesium. In addition to having a higher level of biological activity than the metallic implants that are already in use, the properties of magnesium make it possible for it to reduce the stress-shielding effects of the implant. Magnesium also possesses these capabilities. Their therapeutic value, on the other hand, was limited due to the fact that the human body contains a chloride solution that is both aggressive and corrosive (Song et al., 2012). This is what caused the magnesium in the body to degrade at such a rapid rate.

This is a result of the interaction between the ionic make-up of bodily fluid and the protein concentration of that fluid.

However, there are very stringent requirements placed on the production processes for high functioning implants. Implants have to be constructed in such a way that their structural integrity is preserved for a period of time that is long enough for the structure to be maintained on its own by the bone that is growing into the implant. This period of time must be sufficient for the structure to be able to be maintained on its own. For the greatest possible fit, high profile accuracies and individualised geometries are required. Additionally, individualised surfaces are required for increased biocompatibility, including improved cell adhesion. Because of the difficulty in machining these three-dimensional structures using conventional methods, it is necessary to develop new methods of production, particularly for the production of intricate and highly precise three-dimensional structures. Machining geometries that have high aspect ratios and microstructures lend themselves exceptionally well to the use of electro discharge machining. After that, the capabilities of cutting-edge EDM process technologies are analysed and appraised for use in medical applications. In addition, research is being done to develop a novel technique for the post-treatment of EDM machined surfaces in the near future. By utilising an electrochemical process, a layer of oxide can be produced on top of the EDM surface. This can be achieved by the process of electrochemical oxidation. This may result in improved interaction with biological tissue, and there is the chance that the rate of magnesium corrosion will be reduced as a result of this. Thus, a production chain that combines electrochemical surface treatment and electrical discharge machining (EDM) would have a high likelihood of producing magnesium implants that are both biofunctional and resorbable.

This is due to the fact that electrochemical surface treatment is defined as the process of applying an electric current to a surface to treat it. EDM is an abbreviation for electrical discharge machining. This is due to the fact that EDM is a process that removes material off the surface of a workpiece by employing the usage of electrical currents.

The process of Electrical Discharge Machining, often known as EDM, is successfully utilised in the fabrication of thin-walled components that are utilised in the construction of moulds, medical devices, and aerospace components. The capacity to process high-hardness materials and complex geometries with high precision is one of its features, along with non-contact machining, non-macro cutting strength, and the ability to machine other advantages. EDM has the capability of machining high-hardness materials and complex geometries, which is the reason for this. Both the amount of energy used and the level of machining accuracy are regarded as key parts of the performance metrics required for the creation of environmentally friendly precision. Because of the consistent increase in energy prices and the global management of environmental issues that are related to energy production and use energy consumption is actually one of the most intriguing concerns that the world faces today (Franco et al., 2016). According to a recent assessment on the state of the world's energy supply, annual global energy consumption was 530 quadrillion British thermal units (qBtu) in 2014, and it is anticipated that this figure will dramatically increase over the course of the next 25 years (Newell et al., 2016). Up until the year 2040, it is anticipated that the global demand for energy would continue to increase in absolute terms by the same amount or even more as it did during the preceding period of many decades, and it is anticipated that this demand will be 726 qBtu. As a result of the significant amount of energy used in manufacturing, which accounts for approximately 37% of the world's total energy consumption and is the source of a significant amount of CO2 emissions, it is imperative that energy efficiency improvements be made in the manufacturing sector in order to preserve the environment (Park et al., 2009). As a result, the focus of a number of recent studies has been on developing methods to reduce the amount of energy required for machining and manufacturing operations. Bagaber et al. (2017) undertook a multi-objective optimization of process parameters in order to reduce the amount of power that was required for the process of dry-turning stainless steel 316. This was done in order to reduce the amount of power that was required for the operation. In addition, Kumar et al. (2017) focused their research on the simultaneous optimization of primary energy consumption response, surface roughness (Ra), and material removal rate (MRR) for ecologically friendly and sustainable machining operations. Regarding the eco-friendly operations of the EDM or WEDM process, Franco et al. (2016) did a comparative energy consumption study between Micro EDM and ultrashort pulse laser drilling. This research looked at the two methods' similarities and differences. They discovered that using micro EDM required a far lower amount of energy than using ultrashort pulse laser drilling. Using a high-frequency bipolar pulse generator, Chung et al. (2015) investigated the effect that inductance had on Micro EDM during their investigation. Their objective was to cut down on the amount of time necessary for machining as well as the rate of electrode deterioration (EWR). In order to increase the efficiency of WEDM, Maher et al. (2015) built an adaptive neuro-fuzzy inference system in addition to the Taguchi method. Their objective was to achieve this while preserving the highest possible level of surface quality and keeping production costs as low as they could be.

On the other hand, machining accuracy is a strong predictor for the development of green precision and has a direct relationship to the production defect ratio. The total precision of the result is enhanced by the contributions of both of these aspects. These two facets are intertwined and dependent upon one another. In addition, the geometric error brought on by thermal deformation that takes place during the EDM processing of thin-walled components is the primary cause of the production of a high defect ratio as well as the waste of a significant amount of the workpiece's resources. This error takes place because of the thermal deformation that takes place during the EDM processing of thin-walled components. During the electrical discharge machining (EDM) production of thin-walled components, thermal deformation can occur. This results in the observed phenomenon. For instance, Miller et al. (2015) and Zhang et al. (2018) found that thin cross-sections, increasingly complex workpiece shapes (such as square, variable focus reflector, and long beam), produce considerable thermal deformation, which can result in the loss of function of these components. This was discovered that thin cross-sections, increasingly complex workpiece shapes (such as square, variable focus reflector, and long beam). Components that had thin cross-sections were found to exhibit this behaviour, as was discovered. According to the conclusions of their research, issues arise when the cross-sections of the workpieces are extremely small, and the shapes of the workpieces are becoming increasingly complex (such as square, variable focus reflector, and long beam). In order to deburr drilled holes, monitor geometric error in the composite CFRP, and increase the MRR while minimising machining costs and environmental hazards, Islam et al. (2017) have developed a dry EDM that uses gas as a dielectric rather than liquids such as oil or deionized water as a dielectric. This enables the dry EDM to deburr drilled holes, monitor geometric error in the composite CFRP, and increase the MRR. This enables the dry EDM to deburr drilled holes, monitor geometric error in the composite CFRP, and increase MRR all at the same time. Because of this, the device is able to deburr holes that have previously been bored.

Nevertheless, the determination of the optimal machining parameters would be a significant contributor to the improvement of the surface finish. These process parameters, which directly contribute to the effect of machining characteristic and energy consumption, include peak current, pulse-on-time, pulse-off-time, servo voltage, and servo feed. Therefore, the relationship between the process parameters and the machining effect is considered to be extremely important when milling magnesium alloy using EDM. Focusing on the relationship between the input parameters of the machining process and the influence of energy consumption on thermal deformation in magnesium alloys produced by electrical discharge machining (EDM) is an efficient technique to tackle this state of the problem.

1.2 Problem Statement

Electric Discharge Machining **(**EDM) technology has proven to be very efficient in machining biodegradable materials especially Magnesium alloy by evaluating several issue associated with the machining method. Mostly, these problems are related to surface finish, electrode wear and micro cracks which in the end resulted in poor surface finish, low mechanical strength and others. However, the formation of micro geometric error was found on the machined dimension of Magnesium alloy even though as we know EDM is highest accuracy machining. Controlling the accuracy of biomedical component dimension is a most important criterion which it will be affect the component workability. Improper workability of biomedical component will bare to the high shear stress and strain and finally decrease the component durability. These phenomena indicate the same important criteria to consider as surface roughness which it will control corrosion rate but an accurate dimension can increase workability of the component.

There are a number of factors that can have an effect on this problem, however after taking into account the characteristics of the EDM process and the micro geometric inaccuracy that might be caused by thermal deformation. The ever increasing complexity of the workpiece's shape causes a substantial amount of heat distortion, which might lead to the inability of these components to function properly. In addition, the geometric error brought on by thermal deformation that takes place during the EDM processing of thin-walled components is the primary cause of the production of a high defect ratio as well as the waste of a significant amount of the workpiece's resources. This occurs because thermal deformation takes place during the EDM processing of thin-walled components. Despite this, it is difficult to control machining performance when all we are doing is reducing the thermal deformation by controlling EDM parameter (peak current, voltage, pulse on-time, and pulse off-time). This is because thermal deformation is related to the amount of energy that is being consumed. Both variables are exactly proportional to one another in situations when there is little energy consumption used and where there is less thermal deformation.

Electric discharge machining is regarded to be an environmentally friendly process, and one of the performance measures for this process is energy usage. Other key indications include machining precision (EDM). Therefore, it is necessary to investigate the post-machining features of magnesium alloy in order to lower energy consumption while simultaneously increasing productivity and surface quality to the greatest extent possible at the lowest possible cost in order to ensure sustainable manufacturing. As a result, the purpose of this research is to improve the performance of machining by lowering the amount of energy consumed and determining the most effective machining feature.

1.3 Objectives

The objectives of this study were as follows:

1. To investigate the effect of EDM process parameters on surface roughness, material removal rate and energy consumption of Magnesium alloy.

2. To optimized and validate the machining parameter prone to the energy saving and the best machining characteristic.
3. To develop a prediction model of EDM parameter on Magnesium alloy by using Response Surface Methodology (RSM).

1.4 Scope of Study

The following is what this study was able to cover:

1. Biodegradable AZ31 Magnesium alloy was as material (Mg 97%, Al 3.5%, Zn 1.4% and Mn 0.2%). Refer table 1.4 for physical properties.

2. The controlled machining parameters were limited to peak current (10~14)A, pulse-on- time (2~6)μs and pulse-off-time (10~30)μs.
3. The response variable such as surface integrity, material removal rate and energy consumption analysis were investigated.
4. Design of Experiment (DOE) approach was used to analyze a two-level full factorial design and RSM

1.5 Significant of the Study

The result obtained from this research would help to improve the machining performance specifically in EDM of Magnesium alloy. Since Magnesium alloy is widely used as biodegradable surgical implant, delicate machining and good surface finish are required. Therefore, the identification of significant parameters in EDM of Magnesium alloy would contribute in achieving the minimum energy consumption usage during discharge.