Experimental investigation and finite element analysis of Magnesium Alloy (AZ31B) in Micro Electrical Discharge Machining (µEDM)

Z Izzuddin and M Azuddin
Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia

E-mail : azuddin@um.edu.my

Abstract: Electric discharge machining (EDM) is a non-conventional machining use thermal energy from overheated electron source to remove small portion of material. EDM process has an advantage on high geometric complexity and micro leveling of dimensioning. The present of thermal energy to eliminate the unwanted material in EDM are highly depending on heat affected zone. This can contribute to decreasing of the product quality with surface roughness and micro crack existing after machining. Magnesium alloys (AZ31B) material has the special characteristic to explore the heat distribution effect on the heated surface. Finite element analysis with heat flux Gaussian boundary condition is applied to understand the governing equation of the heat behavior. At the same time, finding the size of spark created on the AZ31B gap is studied. The ANSYS software applied to simulate the heat distributes on the AZ31B surface. The simulation of ANSYS indicates potential zone of material removal through heat distribution. The simulation is compare to the actual experimental of µEDM and finds the similarities. The heat distribution on AZ31B with different size of spark shows a good agreement between simulation and experimental results.

1. INTRODUCTION

Electric discharge machining (EDM) is the non-conventional machining process use thermal source energy to remove material. The EDM process melts small portion of workpiece by electrical discharge spark generated from the machine controller. The discovery of EDM from Joseph Priestly on electrical discharges sparks are the effect from erosive behaviour. Lazarenko exploited the theory and construct a controllable machining process by vaporing material from surface of metal in 1943 [1]. The Lazarenko EDM system used resistance–capacitance type of power supply, which was widely used in the 1950s and later served as the model for successive development in EDM system [2]. In 1980s, EDM is more efficient by integrating the computer numerical control (CNC) in their control system [3]. Later, a lot study was conducted to understand the erosion mechanism of the workpiece and tool [4]. The finite element analysis (FEA) modelled by Vishwakarma et. al [5] discusses the material removal rate (MRR) of Al6063 with metal matrix composite (MMC) where vastly apply in various industries. The concern of heat flux from tool and generate numbers of spark shoot to the workpiece are calculated. FEA was apple to verify the result from conducted experiments. Pritam & Sahu [6], study the EDM process by introducing a mathematical model of thermal energy equation in heat transfer.

Exploration on potential EDM on Magnesium alloy (AZ31B) will enlarge their capabilities in applications. For example, human body has been established to require up to 375 mg of magnesium
Therefore, the potential of magnesium alloys to be new biodegradable implant is highly acceptable. AZ31B is an ideal alternate material in medical industry since the density of magnesium is slightly with human cortical bone density [9]. On the other hand, melting point of AZ31B is 900°C. Therefore, the heat effecting zone of other commonly used as EDM material is comparable to the AZ31B. However, machining of AZ31B using a conventional methods such as milling, turning and drilling will cause formation of cracks, built-up edge and chatter. The most important precaution need to consider while machining magnesium alloy is that the formation of fine chips and the dust is highly flammable [10]. This study will focus on EDM machining of AZ31B and comparison with FEA simulation. The objectives of this work are to study the AZ31B heat distribution from electric discharge machining. Then, evaluate the spark produced by EDM and compare with the simulation result.

2. EXPERIMENTAL SETUP AND PROCEDURES

2.1. Experimental setup
EDM experiments have been carried out to investigate the AZ31B performance using Portable Electric Discharge Machine (PEDM-02) as shown in Figure. 1a. PEDM-02 capable to run normal EDM process, but it the best on performing µEDM process which one spark produces only at a time. The workpiece material used for the study was AZ31B and Copper was used as tool electrode [11]. The size of workpiece samples was 30mm x 10mm x 5mm and 0.5 mm diameter copper electrode was used for the experiments. Tables 1 show properties of AZ31B workpiece and copper electrode, respectively.

![Figure 1. a) Portable Electric Discharge Machine (PEDM-02); b) Process of µEDM with AZ31B and Cu](image)

| Properties (unit)          | AZ31B | Cu     |
|---------------------------|-------|--------|
| Density (Kg/m3)           | 1770  | 8640   |
| Melting Temperature (K)   | 878.15| 1356   |
| Evaporation Temperature (K)| 1373.15| 2840  |
| Thermal Conductivity (w/mk)| 100   | 391    |
| Specific Heat (j/kgK)     | 990   | 376.812|
| Latent Heat of fusion (j/kg)| 0.35 x10⁶| 0.213  x10⁶|

2.2. Experimental Procedure
The AZ31B workpiece specimen was slot into the PEDM-02 fixture and Copper electrode inserted
into the tool holder as shown in Figure 1(b). Then, a dielectric fluid which is distiller water is entering to the tank at specific level. The parameter settings of EDM are cutting speed, depth of cut, and delay time as 5mm/sec, 0.2mm and 0 sec respectively. The speed is the time taking of electrode to reach the sparking zone. It set to 5mm/sec in order give enough time on the capacitor to fully charge. The depth is set to the 0.2mm and it necessary to produce one shot of a spark. The capacitor size was varies from 1, 47, 100 and 220µF for generating various size of spark. The data from generated spark size on workpiece are observed through digital microscope and measure the crater on the workpiece after the EDM process. The data collected was size of crater create and image of the mark area after process.

2.2.1 The effect of capacitor on single spark radius
In this experiment, the AZ31B workpiece is test with single spark and various capacitor values to translate on different size of spark radius created. The AZ31B workpiece undergo EDM process with a single spark produce and restarts again for five times at different location on the same workpiece. Therefore, the workpiece will have five-mark points at different locations. All procedure is repeated to the different of capacitor value.

2.2.2 The size of crater on AZ31B
The procedure of EDM process was done in complete cycle, means the EDM on 0.2mm are proceed to the end. Each workpiece are repeats to three different locations. By the time the process complete, the machine at reset other initial condition and again the capacitor change to the different value. When all procedure completes the data was collected and measure by digital microscope.

3. MODELLING PROCEDURE USING ANSYS
Numerical modelling of EDM process is based on electrical energy conversion into thermal energy which is responsible to melt the material. The mode of heat transfer in solid is through conduction whereas between the dielectric and workpiece is through convection. In the present study discharge behaviour within spark region is modelled as Gaussian distribution. According to this model it is assumed that 40–45% of total heat is distributed to workpiece. The mathematical equation that governs the heat transfer is used to describe the state of heat transfer in the EDM process [12].

3.1. Thermal Modeling
The EDM simulation generate on axisymmetric nature due to the heat transfer on tool toward workpieces. The transient of nonlinear thermal analysis of the single spark perform to obtain the heat boundary [13]. However, there are assumptions are made to present the analysis as feasible mathematically:

- The workpiece domain is considered to be axisymmetric
- The workpiece material is quasi homogeneous in composition
- The heat transfer to the workpiece is by conduction
- Effect of body force and inertia in the time of stress development is considered to be negligible.
- Flushing efficiency is considered 100%
- Before machining the workpiece is stress free
- The heat sources on the surface of the workpiece assumed to have Gaussian distribution of heat flux.

In heat conduction transfer of tool and workpiece the governing equation is apply.

\[ \frac{\partial}{\partial r} \left( k \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( K \frac{\partial T}{\partial z} \right) = \rho C_p \frac{\partial T}{\partial t} \] (1)
Where:

\[ \rho = \text{density} \]
\[ C_p = \text{specific heat} \]
\[ K = \text{thermal conductivity} \]

The plasma distribution on avalanche electron to the workpiece surface in EDM assumed as uniform disk source [14]. Gaussian heat distribution is more realistic for the analysis [15]. Half of workpiece consider since the analysis take axisymmetric model. Figure 2 shows the domain of workpiece with boundary condition load. The surface takes heat flux of Gaussian distribution and boundary (A) receive the heat from spark radius of electrode. The present of dielectric on the top surface count the convection mode of heat transfer on boundary (A) either on boundary (B) and (C) due the distance of spark is far. On boundary (D) heat transfer are 0.

![Figure 2. Boundary condition of model](image)

This boundary condition can represent by

\[ K \frac{\partial T}{\partial z} = Q(r), \quad R < r \text{ for boundary A} \]  
\[ K \frac{\partial T}{\partial z} = hf(T-T_0), \quad R > r \text{ for boundary A} \]  
\[ K \frac{\partial T}{\partial n} = 0, \quad \text{boundary B, C and D} \]  

In this study the Gaussian heat distribution for heat flux in analysis

\[ Q(r) = \frac{4.50^2 PV I}{\pi R^2} \exp \left\{-4.50 \left( \frac{r}{R} \right)^2 \right\} \]  

Where \( P \) is heat of distribution in percentage, \( V \) the voltage and \( I \) is the current. The \( P \) value determine by Yadav et al., [15] is 0.08 and the value are always used by the study for EDM. Heat flux at maximum when \( Q(r) \) at the increase radius. Calculation of spark radius important and considering energy release from single spark. The equation gives [16]

\[ E_{sp} = IxVxt_{on} \text{ and } E_M = W_M IxVxt_{on} \]  

Where

\( E_{sp} \) = energy spark
\( E_M \) = energy absorb by material
\( I \) = pulse current (amp)
\( V \) = gap voltage
\( W_M \) = fraction energy absorbs by material
\[ t_{on} = \text{pulse on (\mu s)} \]

By combine heat flux equation and energy spark equation the R will be

\[
W_MxIxVxt_{on} = \frac{4.45 \, W_MIV}{\pi R^2} \exp\left(-4.45 \left(\frac{r}{R}\right)^2\right) \quad (7)
\]

\[
R = \sqrt{\frac{4.45}{\pi I t_{on}}} \quad (8)
\]

3.2. Simulation with ANSYS

The thermal affected zone is divided in two type condition, heat transfer by heat flux and convection. In order to access the accuracy and efficiency of the FEA, the heat distribution model follows the Yogendra [17] procedure as reference template. The AZ31B material properties set through all analysis in ANSYS is from Chen et. al [18]. The procedure develop finite element in ANSYS are shown by these steps.

Step 1: Start ANSYS Mechanical APDL application
Step 2: Units S.I
Step 3: Analysis method: Thermal, h method
Step 4: Type of element: Two-dimensional with 4 node quadrilateral element
Step 5: Define properties:
Step 6: Created domain
Step 7: Define Mesh: 0.0005 due to the heat influence in \( \mu \)EDM by concentrated area.
Step 8: Define Analysis:
Step 9: Define Load and boundary condition
Step 10: Solve the load and get result
Step 11: Plot require result obtained.

4. RESULT AND DISCUSSION

The ANSYS simulation finds the heat distribution on the AZ31B workpiece. The analysis of thermal distribution is indicated in color zone. This color zone showed the area on workpiece affect in the EDM process. On the other hand, the experiments were conducted to investigate the behaviour of thermal affect in actual EDM machining condition. The result from simulation and experimental were presented.

4.1. Heat Distribution on Simulation

From the simulation, the red color indicate the critical zone where understand as melting zone of workpiece. The orange and yellow zone indicates the burning area of the workpiece surface. The figure 3 shows heat distribution zone on the AZ31B on different size of spark radius. The simulation shows the trend of increasing red zone on heat simulation toward the increasing of capacitor capacity. The highest temperature recorded in the AZ31B workpiece are 3268K and the remove of material start at 3000K and above. The temperature represents the heat flux from the tool has significant value of the spark radius produced. The numbers of nodes indicate the spark radius simulate the contact workpiece might experience.
4.2. Crater Zone on AZ31B

The single spark on experiment by PEDM-02 using AZ31B workpiece and Cu electrode create the crater. This removal material phenomenon is by assuming all the molten and vaporized materials are removed after the discharge spark occur. The crater geometry can be estimated by the melting isothermal behaviour [19]. In this experiment, the crater creates on AZ31B workpiece surface as shown in figure 4. There are two different measurement are taken, the radius (Figure. 4a) and circumference (Figure. 4b) of heat zone affect after spark generated. On radius, the surface loses some material and shown as a crater. For circumference, the surface showed burning area on heat zone affect. It found at the outer of the crater and can see as a ring surrounds the crater. As the result in the figure 5 shows the dimension of radius and circumference. The experiment shows increasing trends for crater as the capacitor value increase.
The crater are more visible on the AZ31B workpiece surface when apply experimental condition as explain in section 2.2.2. From the process, the result shows similar output and the crater measure much clearer of crater sparking and heat affected zone. By the result, measurement of radius and circumference of both condition are measured. The figure 5 shows example of measurement taken for radius and circumference of spark for actual experiment conducted.

Figure 5. (a) circumference size of AZ31B samples (b) radius of AZ31B samples

Figure 6 shows a characteristic of crater on EDM machining, where the radius of crater is below the tool size but increase when the capacitor value increase. It also happens to the circumference increase parallel to the capacitor value. The trend of heat distribution in experiment also increases as the size of capacitor increase. The charge store and release in capacitor has significant contribution on the heat flux intensity. However, larger capacity of capacitor causes the slow EDM process, which is not favorable in machining process. The parameter optimizations in EDM are crucial for getting a good quality of machining. The selection of capacitor, speed, delay time and tool electrode need to be considered carefully in order to produce good quality of part.

Figure 6. Crater Distribution of EDM experiment

4.3. Crater Zone simulation on AZ31B.

Figure 7 shows the comparison between radius of crater on ANSYS simulation and the experiment. The different off on single node and 1µF tend give huge different. On the other hand, on 10 nodes (100µF) and 20 nodes (220µF) give significant different on both data 30% - 40% different. However, the five nodes (47µF) the different is about 8%. By comparing both methods, it shows the trend on the increase size of spark radius will increase the heat affected zone on the workpiece. The simulation in ANSYS give the characteristic of heat affected zone. However, in actual process, it can see the phenomena of spark burning a non-uniform shape.
5. CONCLUSION

In EDM, the thermal energy is utilized to remove the material in melting and evaporation process. The increasing heat on the Gaussian distribution model will result in increasing a spark radius on the workpiece surface. The analysis of finite element shows how the heat distributed on the workpiece surface. The Gaussian boundary condition demonstrates the finite element analysis in mathematical ways to present the heat zone of EDM application. The ANSYS simulation gives the initial prediction on how the heat will behave on workpiece material. These can reduce EDM setup time for optimal process parameter. Also, it will reduce the waste of workpiece and tool material. Therefore, as a comparison with actual experiment, the finite element analysis shows how the heat parameters

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Figure 7 Comparison on simulation and experiment
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