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DEVELOPMENT OF ELECTRIC DISCHARGE MACHINING (EDM) USING SOLENOID ACTUATOR FOR EDUCATIONAL PURPOSE

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Abstract
The increasing number of materials with variation in properties, especially hard-to-cut, leads to the need for an advanced machining method to process such material. Electric Discharge Machining (EDM) is one of the advanced machining methods widely used for hard-to-cut alloys. The EDM process uses an electrode as the conductor of electrical current to erode the metal alloys and is supported by other components. Due to EDM's high cost and high energy consumption, developing a low-cost EDM and simpler EDM setup is necessary, especially for educational purposes in laboratory activity. However, the EDM design and setup required to produce the desired "spark" have always been a challenge for researchers and manufacturers. In this research, a small-scale EDM setup was built. A solenoid actuator is used to generate simple mechanical movement. The movement is used to control the gap between the workpiece and the electrode to produce a spark. The solenoid actuator is used because of its low cost and simple mechanism. The proposed EDM setup is successfully fabricated and works appropriately by generating sparks and a hole cavity during the process. There are six cavity holes produced in mild steel workpiece during the experiments with various parameters such as current (5A, 7A, and 10A) and frequency (10 Hz and 20 Hz). The varied parameter shows that the higher current and lower frequency removed more materials. In contrast, the higher frequency produced a better quality of the cavity hole. However, the lack of flushing quality on the material debris during the process results in the formation of excess metals around the edge of the hole.

Keywords:
Cavity;
Electric Discharge Machining (EDM);
Solenoid Actuator;
Spark;

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INTRODUCTION

The need for a lightweight and strong material used in aerospace and aeronautics led to the invention of new alloys. However, these new alloys, such as titanium and nickel alloys, are challenging to machined (hard-to-cut) [1]. Electric Discharge Machining (EDM), as one of the advanced machining methods, has the advantage to be applied for hard-to-cut materials [2][3]. The EDM uses electrical sparks to erode the surface without exerting any contact force to the workpiece [4, 5, 6]. In addition, EDM can also be used for machining biocompatible materials such as Ti-6Al-4V used for various medical implants such as orthopedic and dental [7]. However, despite many advantages, the EDM process also induces residual stress that can be harmful to the machined components. Therefore, the residual stress needs to be considered and minimized [8].

Conceptually, the EDM process requires an electrically charged electrode as the cutting tool and a submerged electrically conductive workpiece inside a dielectric fluid connected to the ground [9]. There is a small gap between the electrode and the workpiece called the discharge gap (0.005-1 mm) to initiate the spark [10]. In order to control the discharge gap, an up-down movement of the electrode is required by attaching the electrode to an actuator. Figure 1 shows a schematic of the EDM machine and the erosion process that takes place in the discharge gap.

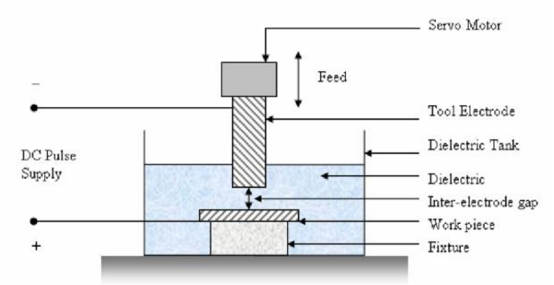
Furthermore, EDM mainly consists of few elements, which are:

a. ***Electrode***.

The electrode is mostly made from copper, brass, or graphite material in cylindrical shape or wire with various diameters [11]. The quality of cutting depends on the material properties of the electrode, such as its electrical conductivity, melting point, and chemistry.

b. ***Power Supply***.

The source of energy to generate the spark comes from a power supply. A power supply consists of a transformer to reduce the amount of voltage from a larger electrical source and a converter to convert an alternating electrical current (AC) into a direct electrical current (DC) [14][15]. The direct current (DC) is used due to its stable behavior and easiness to control [16].



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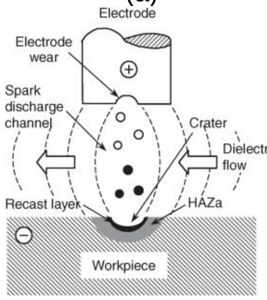


(b)

Figure 1. a) Schematic of an Electric Discharge Machining (EDM) machine [12], b) Schematic of an erosion process in the discharge gap [13]

c. ***Current Controller***.

A current controller or pulse generator is a wave manipulator which produces a pulsating (ON/OFF) wave of electrical current out of a DC input [17]. The pulsating current is used to control the discharge gap [18]. There are three important parameters of a pulse generator to be controlled: discharge and non-discharge time, current magnitude, and wave frequency, as shown in Figure 2.

d. ***Dielectric Fluid***.

A dielectric fluid is an electrical isolator element needed during spark ignition [19]. It can be in the form of oil, kerosene, or distilled water and acts as a flusher or cleaner of the debris produced during the machining process. There are several important parameters when selecting a dielectric fluid for operation, such as dielectric strength, viscosity, color, and odor.

In addition, material removal in EDM usually occurs due to heat energy generation that evaporates or even ionizes the material in a small narrow area. The material removal rate is given by the formula [19]:

$$MRR = \frac{WRR}{T} \quad (1)$$

where,
MRR = Material Removal Rate (mm^3/min)
WRR = Workpiece Removal Rate (mm^3)
T = time (minute)

The cavity produced by a single spark can be assumed in a hemispherical shape with a radius r, as shown in Figure 3.

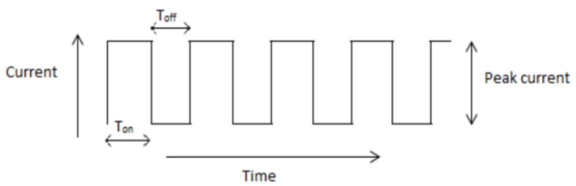


Figure 2. Pulse waveform of pulse generator [17]

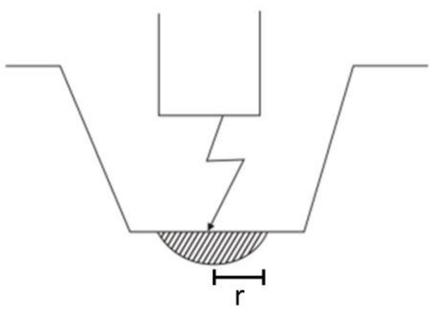


Figure 3. Schematic representation of cavity formation in EDM [19]

Hence, the workpiece removal rate can be expressed as the following [19]:

$$WRR = \frac{2}{3}(\pi xrxrxr) \quad (2)$$

The energy content of a single spark (Es) is given by:

$$E_S = VXIXT_{on} \quad (3)$$

where,
V = Voltage (V)
I = Current (A)
T_{on} = supplied current time (minute)

The heat energy is partially lost in dielectric fluid, and the other goes to the workpiece to remove the material. The heat transferred to the workpiece is expressed (E_w) as:

$$E_W = kXE_S \quad (4)$$

where,
The k is the heat conduction coefficient.

Due to the above theory, it can be assumed that the material removal in a single spark is proportional to the spark energy given by:

$$WRR = gXE_S \quad (5)$$

where,
The g is a constant value.

Due to its advantages and simple working principle, many experiments on making homemade EDM machines have been conducted and reported for a small-scale machining process at home and laboratory [20]. There are many ways to develop EDM in terms of design and configuration to produce the desired electric spark, such as by modifying rotary disk electrodes [21], applying a piezoelectric actuator [22], and combining with ultrasonic vibrations [23]. The electric spark is generated as the result of the presence of a gap between an electrically charged workpiece and electrode [5][6]. At the same time, a movement from an actuator or a servo is mostly reported used to control the gap, for example, in the usage of the piezoelectric actuator [22] and servo-mechanism combined with ultrasonic vibration [23].

Even though the servo usage as the gap controller is widely used, it has a disadvantage that requires additional control systems with complex configurations such as adaptive fuzzy controller [23] and servo control system [24]. In addition, the development of EDM using solenoid has a promising in order to produce spark and hole cavity with simpler mechanism and configuration.

As a result, the usage of a solenoid actuator is proposed as one of the many ways to develop the EDM with an actuator to control the gap [24].

Therefore, this paper aims to design and fabricate a hole popper EDM setup using a solenoid actuator. The fabricated EDM setup will be tested by producing discharge spark and cavities on the metal workpiece using various parameters and subsequently analyzing the results. Qualitative and quantitative analyses are conducted in this paper. This setup can be useful for teaching and learning in manufacturing processes courses at the university level.

METHOD

Experimental Setup

There are mainly three steps conducted in this experiment. In the first step, the EDM setup is designed. Secondly, the structure is analyzed using finite element analysis (FEA), and lastly, the setup is tested by creating cavities.

Design and Development of the Machine

The proposed EDM setup is shown in Figure 4. In this setup, the solenoid actuator is used to control the up-down linear movement of the electrode. The required gap between the workpiece and the electrode to produce a spark is expected to be achieved.

The solenoid actuator is used because of its low cost and simple mechanism [25]. Solenoid actuator is an electromagnet device widely used in automotive, biomedical, and manufacturing industries with a helical shape coil wound that has a moveable ferromagnetic part (plunger) in its center, as depicted in Figure 5 [26].

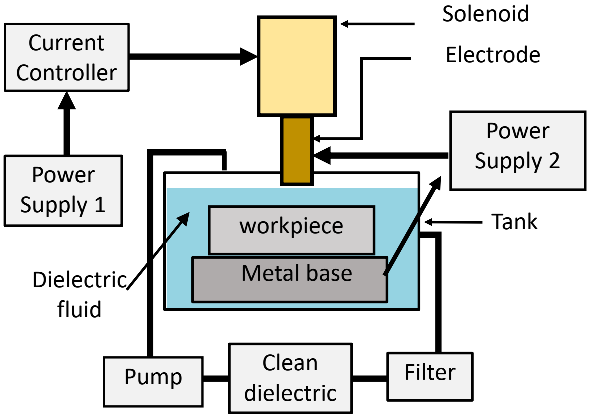


Figure 4. Schematic working process of the EDM machine

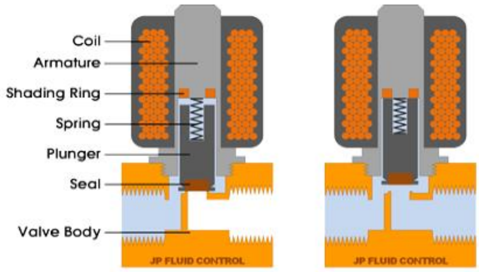


Figure 5. Schematic representation of a direct operated solenoid valve (2/2-way, normally closed) [29]

Solenoid actuator can be used for the linear compressor in the refrigerator [27], diesel engine injector [28], and valve [29]. Using the principle of the generated magnetic field from flowing electrical current through the winding, it exerted a force to the plunger to move to the upper position inside the casing of the solenoid [29]. As soon as the electrical current supply is cut off, the mechanical part represented by a spring pushes the plunger back to its initial lower position [26]. The electromagnetic force is large enough to compensate for the combined spring force and the static and dynamic pressure forces of the medium so that it can move up and down alternately [30].

Two power supplies are used, which are power supply 1 & power supply 2. Power supply 1 performs as the main source of solenoid actuator, which goes through the current controller. It requires at least 220 ACV to 0-24 DCV capacity power supply for power supply 1 since the solenoid actuator only has 24 DCV maximum voltage circuit capacity. Power supply 2 acts as the main energy source to generate the spark by connecting the positive side to the electrode and the ground to the workpiece. It requires at least the same specification as the power supply 1 or higher.

Arduino relay module is used as a part of the current controller based on the configuration in Figure 6 with Arduino as the microcontroller. However, this relay module is unity with solenoid as an actuator which acts as the controller of the input signal together with Arduino. It has 5-12 DCV of power input with 1 channel normally open and close. This module has an optimum operating range up to 20 Hz with a 50% or duty cycle. The configuration between relay module, Arduino, solenoid, and power supply is shown in Figure 6.

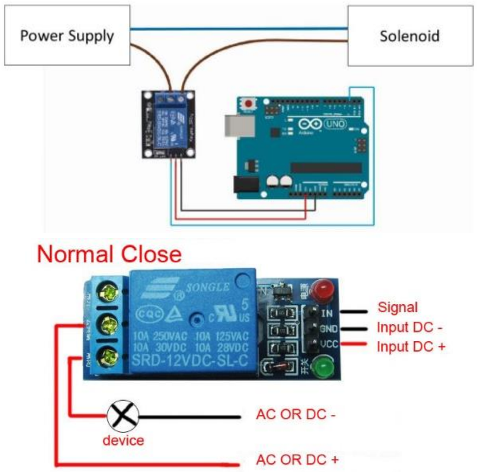


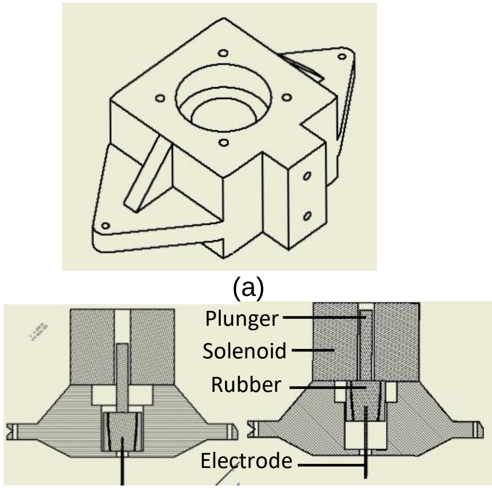
Figure 6. Circuit map or configuration of relay module, Arduino, solenoid, and power supply.

Figure 7. Solenoid valve DC 24 V/0.42 A

The solenoid comes from a solenoid valve part with the capacity of DC 24 V/0.42 A, as shown in Figure 7. It consists of 2 main parts: the solenoid (upper part) and the plastic channel (lower part).

A modification of the plastic channel is made using 3D printing to hold the electrode stably, as depicted in Figure 8. It also consists of an additional 3D printed tube with cone-shaped rubber inside. It acts as the direct holder of the electrode that is attached to the plunger. This holder transfers up and down movement by the plunger because of the magnetic force of the solenoid to the electrode.

A stand holder made of 5 cm x 5 cm hollow steel and a 2.5 cm diameter cylinder is used to place the solenoid actuator, as illustrated in Figure 9. The holder is able to move up and down manually to adjust the height of the solenoid to the workpiece. An extension slider arm with another holder is added to keep the 0.8 mm copper wire electrode straight using a 1.4 mm capillary pipe to channel the electrode wire at the top.

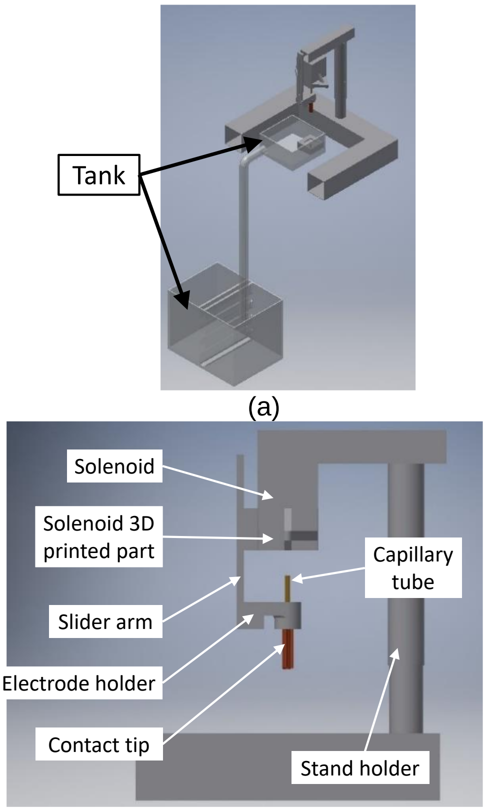


(a)

(b) (c)

Figure 8. a) 3D printed part, b) Down position, and c) Up position

The bottom part of the holder also consists of a brass contact tip as the guide for the electrode to the workpiece. The workpiece is attached to a steel workpiece bed and submerged into distilled water that acts as the dielectric fluid inside a clear acrylic tank.



(a)

(b)

Figure 9. a) Complete proposed EDM design, and b) Electrode holder component (Side view)

Data Collecting & Analysing

The data of the generated spark and cavity hole produced by the proposed machine setup was collected. Several steps need to be conducted as a preparation for data collecting using the machine.

a. A 5-10 cm of wire electrode needs to be inserted through the contact tip and capillary pipe until it sticks into the rubber inside the holder.
b. There must be around 1-2 cm of the exposed electrode from the contact tip by adjusting the height of the extension holder.
c. A 2 cm x 2 cm mild steel workpiece was placed on top of the workpiece base and dielectric fluid was added to the tank until the workpiece was submerged.
d. The power supply and current controller are applied to the following variations:
   1. Power Supply 1: 12 DCV / 0.4 A.
   2. Power Supply 2: 12 DCV / 5 A, 12 DCV / 7 A, 12 DCV / 10 A.
   3. Current controller: 10 Hz and 20 Hz (50% duty cycle).
e. The experiment time for each cavity is about 60 minutes.

In this project, the result of generated spark was analyzed using the qualitative data analysis method. The brightness quality of the spark was observed in order to determine the working capability of the setup. Direct observation by taking a picture using a camera is used as the data collecting method for the spark result.

On the other hand, the result of the cavity hole was observed using the quantitative data analysis method. First, the cavity holes are observed using an optical microscope. Then, the average diameter of the cavity hole is measured using software image measurement (Picpick image measurement software). Finally, the dimension of the created hole was measured and analyzed. Figure 10 shows the method to measure and calculate the hole diameter.

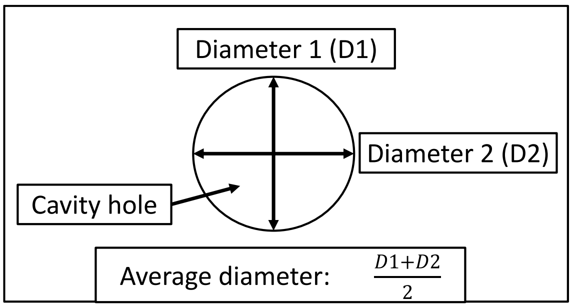


Figure 10. Measurement technique of the cavity hole

Two diameters, namely D1 and D2 perpendicular to each other, were measured. Subsequently, the average diameter was measured by dividing the sum of D1 and D2 by 2. Subsequently, the material removal rate (MRR) was calculated for each cavity hole using (1).

RESULTS AND DISCUSSION

Figure 11 shows the finished proposed EDM setup based on the schematic design as shown in Figure 4 and Figure 9. The data collecting process was fully conducted using the setup.

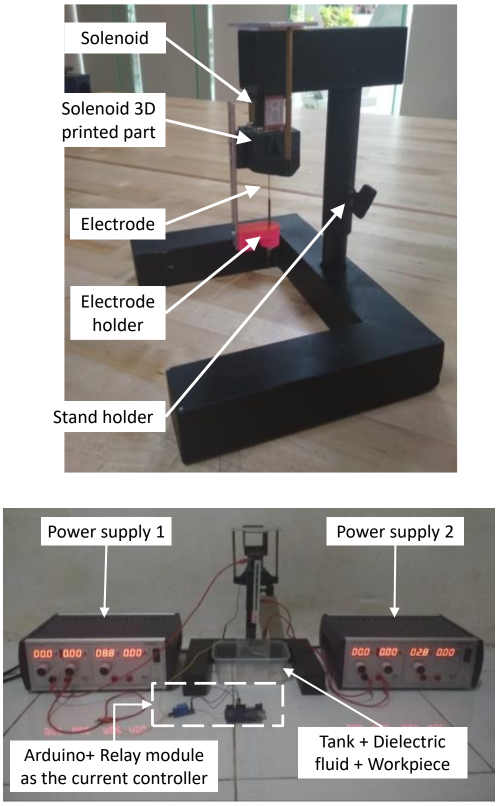


Figure 11. Proposed EDM setup

Structure Finite Element Analysis (FEA) Result

Finite Element Analysis (FEA) has been conducted on the design set up with restricted parameters to analyze the stability of the structure. The fixed boundary at the bottom (x-z plane) of the structure and a 30 N of force as a solenoid load in the negative y-direction were applied, as depicted in Figure 12. Figure 13 shows the FEA result with the critical point of the structure is located on the connection between the upper arm and the vertical cylinder part. However, the safety factor shows that the structure is very safe due to a static load because of the solenoid weight. Furthermore, with a safety factor value of 15, as shown in Figure 14, it can still be considered safe to withstand the other undesired factor, such as the vibration of a solenoid. It is concluded that the setup is successfully fabricated and able to be used for the experiment.

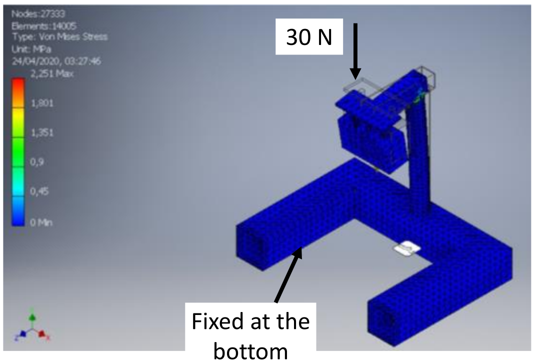


Figure 12. Parameter restriction on the FEA of the designed structure

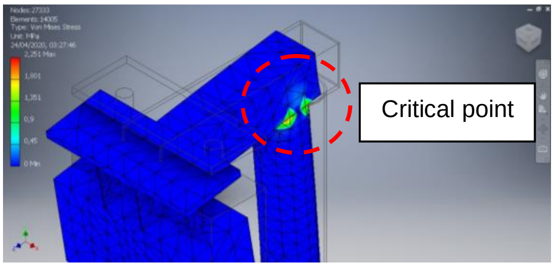


Figure 13. The critical point of the designed structure

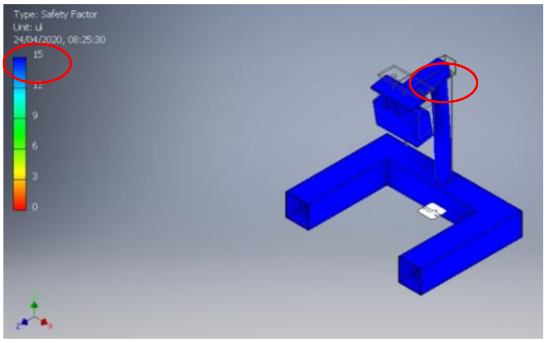


Figure 14. The safety factor result.

Spark Results

The result of the generated spark for each variation sample is shown in Figure 15. It can be seen that both frequencies (10 Hz and 20 Hz) show a similar pattern. As the given power in terms of the electrical current increased, the spark generated becomes brighter. The brighter spark implies more material removed compared with the dimer spark. The given energy is proportional to the material removal represented by the brightness of the spark [19].

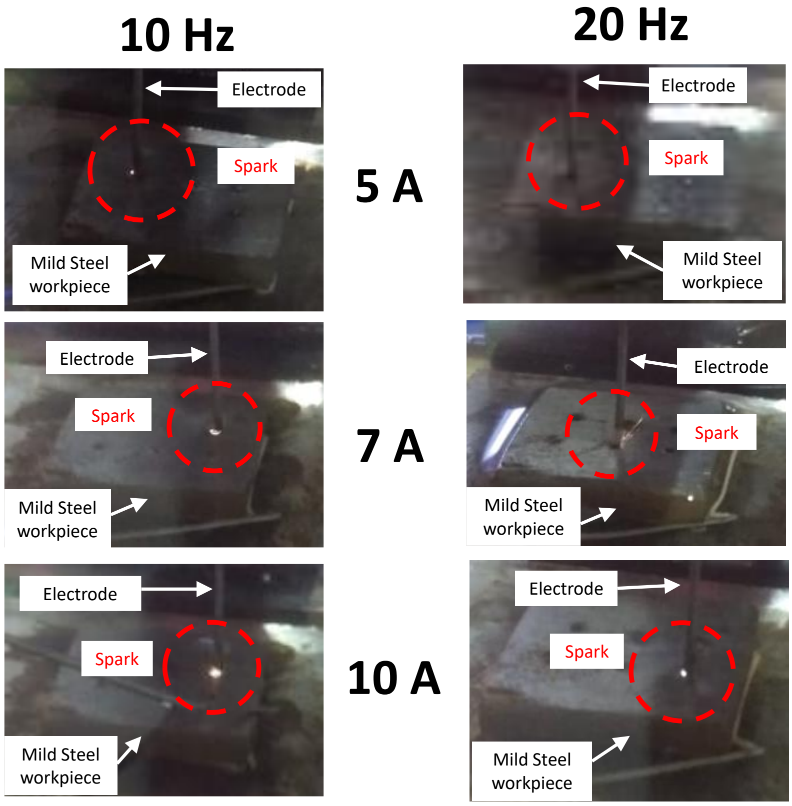


Figure 15. Spark result with frequency 10 Hz (left) and 20 Hz (right).

In addition, the higher frequency produced a dimmer spark while the lower frequency produced a brighter spark. In general, the higher frequency produces more discharge contact between the electrode and the workpiece, but it decreases the discharge time. In contrast, lower frequency gives less discharge contact to the workpiece, yet more discharge time.

Based on the result of the spark, it can be seen that the lower frequency of 10 Hz with 50 milliseconds (ms) of discharge time gives a better result compared to the higher frequency of 20 Hz with 25 milliseconds (ms) of discharge time. However, the result based only on the spark is not sufficient to explain the machining result using the proposed built setup.

Results on Cavity

The result of the cavity hole on the workpiece is shown in Figure 16. In total, six cavity holes are produced as the result of 6 parameter variations. Optical microscope observation was used to analyze the cavity holes from each parameter variation (Figure 17 and Figure 18).

It can be seen that the cavity hole average diameter is larger as the current increased for the 10 Hz frequency (Figure 17). This supports the finding on spark result, which indicated that more material is removed due to spark generation as the current increased. The cavity hole quality in terms of the roundness shape of the hole also corresponds to the amount of the given current. For a smaller given current, the difference in diameter 1 (D1) and diameter 2 (D2) is quite significant. This is due to the lack of power to erode or evaporate the material, resulting in the uneven shape of the cavity hole. However, the measurement of D1 and D2 for a given current of 10 A shows a minor difference.

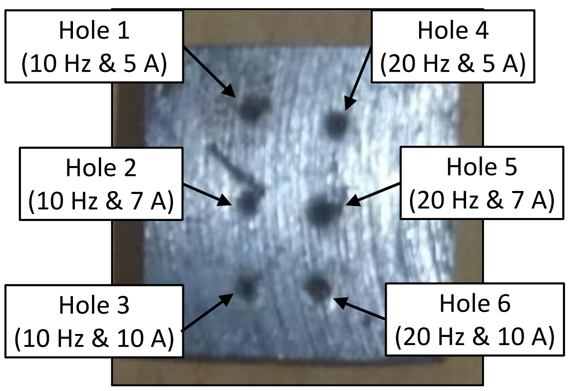
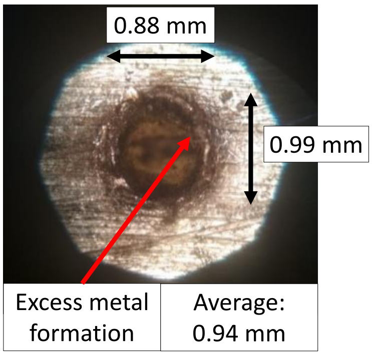


Figure 16. Result of cavity hole on the workpiece



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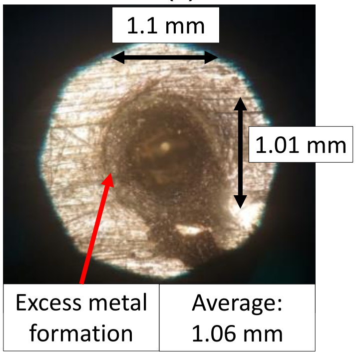

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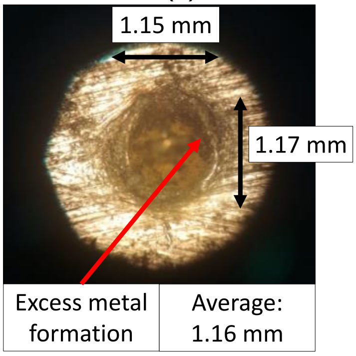
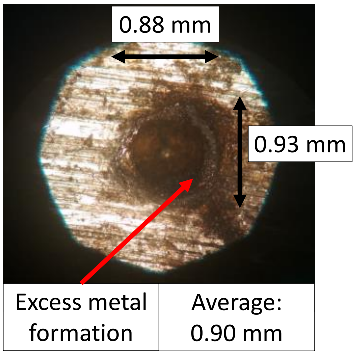


(c)

Figure 17. Cavity result with frequency 10 Hz a) Hole 1 (10 Hz & 5 A), b) Hole 2 (10 Hz & 7 A), c) Hole 3 (10 Hz & 10 A).



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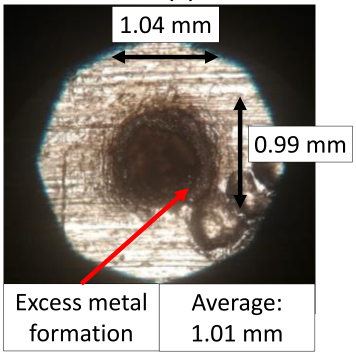

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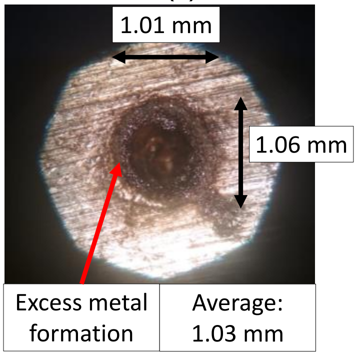

(c)

Figure 18. Cavity result for frequency 20 Hz a) Hole 4 (20 Hz & 5 A), b) Hole 5 (20 Hz & 7 A), c) Hole 6 (20 Hz & 10 A).

Similar results can also be observed for the 20 Hz frequency (Figure 18). The increase of the cavity hole average diameter is along with the increased given current. However, the quality of the cavity hole roundness shape is better than the 10 Hz. Diameter 1 (D1) and diameter 2 (D2) have a small dimension difference using 20 Hz frequency.

It implies that a higher frequency increases the accuracy and quality of the hole. Furthermore, some of the results show an excess portion of the melted electrode on the edge of the hole. It can be occurred due to the lack of fluid flow to flush the remaining debris from the process.

Due to the difficulties of flushing out the remaining material from the cavity hole, it eventually melted and formed the excess metal on the hole's edge.

Material Removal Rate (MRR)

The material removal rate (MRR) and workpiece removal rate (WRR) are calculated using (1) and (2), respectively. The experiment process time is about 60 minutes for each hole. The calculated MRR is shown in Table 1. It can be seen that as the current increase, the MRR is increased for both frequencies (10 and 20 Hz).

Table 1. MRR for 6 holes

Hole	Frequency (Hz)	Current (A)	MRR (mm^3/min)
1	10	5	0.0036
2	10	7	0.0052
3	10	10	0.0068
4	20	5	0.0032
5	20	7	0.0045
6	20	10	0.0048

However, the 10 Hz frequency has a larger MRR compared to 20 Hz. This result is consistent with the sparks result and the cavity result. Therefore, more materials are removed when using a 10 Hz frequency.

CONCLUSION

The fabrication of the proposed EDM setup using a solenoid actuator is successful and can be used to experiment. The proposed EDM setup using a solenoid actuator can also work correctly by generating sparks during the process and producing a whole cavity. The various parameters show the higher current given; the more material removed. In addition, the lower frequency (10 Hz) produced higher MRR compared to 20 Hz. In contrast, the higher frequency (20 Hz) produced a better quality of the cavity hole. This EDM setup using a solenoid actuator can be used for the teaching and learning process in university for manufacturing process courses. Lastly, the lack of flushing quality on the material debris during the process results in the formation of excess metal around the edge of the hole. Therefore, an improvement in the flushing process is needed to avoid any excess metal formation.

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