Finite element analysis of magnetic field assisted wire electric discharge machine

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Abstract. One of the non-conventional manufacturing processes includes Wire-Electrical Discharge Machining (WEDM). It has made exponential growth in its manufacturing capabilities during the last decade but still, this method is not utilized to its full potential. One of the major problems faced in WEDM is arriving at the micro level parameters such as Plasma channel. It spread towards in radial direction. In order to overcome this problem, electro-magnetic field is applied externally and its effect is studied on various responses. In this paper, the different possibility of the single-discharge is investigated by changing parameters such as magnetic field, current, pulse on-time, voltage, and without magnet etc. In WEDM, the electromagnetic field aids in increasing the depth and reduced crater diameter marginally but considerably better equality in the material erosion by confining the plasma in a radial direction (due to the applied magnetic forces). To study the transient heat distribution and crater shapes FEM analysis has carried out. The WEDM without any external magnetic field produces results which are undesirable in terms of energy efficiency due to poor thermal distribution caused by Electrostatic repulsive forces. The outcome of this can be improved by applying external electromagnetic field which leads to the reduction of electrostatic repulsive forces. The ANSYS 18.1 is used for analyzing the transient temperature, the shape of the crater.

1. Introduction

Wire Electric discharge machining (WEDM) is a non-traditional machining process. It is capable of machining geometrically complex and hard materials. It consists of thermal energy in the form of spark for machining complex parts of industrial applications. [1] In wire-EDM, the dielectric fluid is alienated due to the presence of voltage between the electrodes. The electricity is supplied in the form of a pulse to generate the plasma channel. It allows the spark discharge. It consists of extreme thermal energy which melts the material and forms crater. It is important to study the shape of crater because it depends upon the behavior of the spark by using electro thermal analysis in FEM. The real sequence of process is not yet understood fully at the micro level. So to understand the behavior of spark the electromagnet field is applied to control it. Many researchers investigated the machining characteristics and its effects by changing the parameters such as the dielectric, pulse duration, etc. [2] In FEM analysis heat source plays a key role. It is divided into three types of heat flux distribution. They are the point heat-source,
disc heat source with a uniform heat flux and the disc heat source with a Gaussian heat flux. The above heat sources are simulated for different kinds of crater shape. [3] Proposed a calculation of the magnetic field effect and first Townsend coefficient. The assumptions are made such that the collision of molecules in gas with the electrons is inelastic in nature and the mean free path is constant for electrons. The application of magnetic field changes the path of electrons into cycloid so that the mean free path will also change. [4] Projected to use the electromagnetic around the plasma EDM to confine plasma extension and improve MRR. [5] Proposed to use mechanical protection of the plasma so it can exert the reverse pressure on plasma block which helps to confine plasma and increase MRR. [17] Proposed that the plasma detention is to consider the effect of oblique electro-magnetic force on the electron beam. [6,16] Studied primary ionization coefficient with electrons. [15] Reported about secondary ionization. [11] FEM based move toward to analyze the spark profile as non-cylindrical.

In this paper, the Gaussian heat flux is considered. Because the microscopic view of the crater has a similar shape of the simulating crater. The Gaussian heat flux is spread towards the radial direction on the surface of the work piece due to the presence of electrostatic repulsive force. It is replaced with time dependent electric field. The dielectric medium breaks down occurs due to critical value being more than its electric field. To control the electrostatic repulsive force, the electromagnetic force has applied.

2. Wire-EDM in Thermo-physical representation

2.1 Spark of Wire-EDM

To study the spark radius and shape are very difficult experimentally even though the significance of the spark radius high due to very small and high frequency of the pulse. [7, 8] Proposed the thermo mathematical studied on the source of heat and various responses of its heat diameter. [9, 10] Proposed the thermodynamic method to study spark radius and temperature variation. [18] Recommended a practical relationship to estimate the spark radius for a chosen couple of electrodes and dielectric. The two important parameters were assumed. They are spark radius and the energy distribution between the electrode and dielectric. [11, 12] Proposed the total power constant fraction is transferred to the electrodes. The majority of theoretical representation imagines the efficiency of ejection equal to 100% the further parameter so far ignored

2.2. Boundary conditions

The crater is formed only when the intense amount of thermal energy is generated in work piece due to contact with plasma channel. It can be superheated the work material. The heat travels from plasma channel to work material. The spark is generated at the location where the tool will be in contact with the work material. The spark is represented in the form of Gaussian heat flux. In this paper the single spark was affected as shown Fig. 1 and accordingly boundary condition is applied. In the WEDM the work piece was immersed in a dielectric medium with the ambient temperature ($T_a$). The top surface of work piece is in contact with the tool and at the remaining sides convection is applied.
2.3. Governing equation

The Fourier governing equation for transient thermal analysis of Wire-EDM in a non-linear process is given in (eq(1)) which works for cylindrical work domain.

\[ \frac{1}{r} \frac{\partial}{\partial r} \left( K_r \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial T}{\partial z} \right) = \rho c_p \frac{\partial T}{\partial t} \]  

(1)

Where Thermal conductivity (K), Temperature (T), Specific heat of work material (Cp), Density (\(\rho\)).

2.4. Heat input

[13, 12] Some of the key factors used to calculate the radius for a single spark of the Wire-EDM model includes heat input, plasma radius and thermo-physical property of the material. The assumptions were made by the researchers such as hemispherical crater cavity with the point heat-source or disc heat source with a uniform heat flux. These types don’t match with the microscopic shape. It is generated on the surface of the anode electrode. [11] In this paper to approximate the heat which comes from plasma on the work piece. It will represent in the form of Gaussian distribution of heat flux.

\[ q(r) = q \times \left( \exp \left( -4.5 \left( \frac{r}{R} \right)^2 \right) \right) \]  

(2)

\[ q = \frac{4.57f_cV_i}{\pi R^2} \]  

(3)

where q is maximum heat flux, \(f_c\) as a total power of spark fraction which is going to an anode, (V) Voltage discharge; (i) Current discharge and (R) Spark radius at work material.

2.5. Spark radius

It is an essential factor for a Wire-EDM process for the thermal analysis. [14] In reality, it is difficult to measure the radius of spark because of an extremely short duration of the pulse (microseconds). [13] The equation for spark radius is based on heat point. The equations are projected by researchers which are not reasonable in real life for the spark. [18] resulted in the equation for spark radius which is in the form of semi-empirical and it is termed as "equivalent heat input radius". It consists of discharge of current (i) and \(t_{on}\) (discharge) (ms) (eq. (4)). When compared to the other proceed ways it is more efficient one. [12] Found that \(f_c\) (0.183) must be selected for superior connection between the analytical results.
Where \( i \) is the current, \( t_{on} \) is the discharge on time.

### 3. Evaluate plasma confinement

[3] The EDM is using the emission mechanism. It has electrons as major charge carriers. In the WEDM process a huge quantity of electrons flows from cathode to anode due to which break down takes place. When an external electro-magnet is applied to the plasma, it causes two major effects such as (1) Plasma confinement and (2) Mean free path reduction. These two effects help to determine the changed parameters of the crater mathematically for a single spark.

#### 3.1. Confinement of plasma

As electrons emitted from a cathode to anode it experiences the electrostatic field in a radial direction. It consists of a number of electrons, charge of an electron, a mass of an electron, the radius of an electron beam; drift velocity is directly proportional to voltage (V). The electron is accelerating \((eV/m_e)\), in the radial direction due to the presence of forces such electrostatic field, self-magnetic field, external magnetic field. The self-magnetic field is formed due to the ampere law and applied Lorenz force at the centre. As an application of external magnetic force, it has added more Lorenz force and takes place at the centre. It confines the plasma channel and reduces the spark radius as well. As the beam reaches to the anode it spreads towards the radial direction due to the domination of radial electrostatic repulsive forces.

To determine the exact radius of electron beam (plasma) at the anode (work piece) then calculated by the time \((T_d)\) taken an electron to travel between electrodes is taken as the ratio of an internal gap and drift velocity. The repulsive forces are ignored. As the current increases, the electrostatic repulsive forces also increase due to which the number of electrons increase. As the voltage increases the drift velocity \((v)\) also increases and electrostatic repulsive force would be reduced. Since the electrostatic repulsive force and self-magnetic field is present in both magnetic and non-magnetic field. But the main difference is caused due to the application of the external magnetic \((b)\).

The reduction in crater radius is given by

\[
R = (2.04e - 3) \times 10^{0.43} t_{on}^{0.44} \quad \ldots \ldots \ldots (4)
\]

Where \( b \) = magnetic field, \( e \) = charge of electron, drift velocity \((v_d) = 10^4 \, \text{m/s},\) mass of electron \((m_e),\) time required \((T_d)\) by the electron to travel between two electrodes.

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**Figure 2.** Magnetic confinement of plasma channel.
[3] The application of electromagnetic field creates the reduction in the mean free path of the electron. It effects in two ways. They are (a) plasma pressure increase and (b) Cycloid path of electron. The plasma pressure increases because of the area of plasma channels confines in a radial direction by application of an external magnetic field. The mean free path reduces due to cycloid electron path of electron by application of external electromagnetic field is perpendicular to the z-axis (or) velocity as shown in fig (3)

![Cycloid path](image)

**Figure 3.** Cycloid path.

Where “E” is the electric field, “v” is velocity and “b” is applied a magnetic field. The speed of a particle is depending on the electric field. The direction of a particle is depending on the electric and magnetic field. Therefore, ionization is increased by the application of external magnetic field which helps to increase the charge carriers and more particles reaches the surface of the work piece in the form of heat flux. It is evaluated by using the ANSYS 18.1 FEM software.

4. Result and discussion

Titanium grade2 properties are thermal conductivity=16.1W/(m-k) specific heat=551(J=kg K) density=4541kg/m³ melting point=1938k ambient temperature=298k, t<sub>off</sub> = 5, Co-efficient of heat transfer of Dielectric fluid= 10,000 (W/mm²K)

4.1. Analysis

4.1.1 Methodology.

To calculate temperature distribution, the Governing equation (Eq. (1)) with boundary conditions Fig. 1 outlined before to solve by FEM. In ANSYS18.1 the 2D work piece with twice the size of spark radius is created for analysis. The element (PLANE 55) with four-noded, thermal solid elements, axis-symmetric, is used for analysis. The material properties such as thermal conductivity, density, specific heat are used. Different probabilities were tested by raising the elements in the mesh. The loads were applied as shown in the boundary condition Fig. 1 and consider that the work piece is place under the ambient temperature (298K). The titanium grade2 material properties are used for analysis. The analytical condition shows the actual working model of wire EDM such as current 4A, voltage 40V and t<sub>on</sub>(30-100ms). To predict the transient temperature distribution and the shape of the crater. The elements which are above a melting point of the material is eliminated in the work piece model as shown Fig. 4 and Fig. 5.
4.1.2 Temperature distribution.

**Table 1:** Numerical readings

| SNO | Voltage (v) | Current (i) | T-on (µs) | Crater radius without magnet (WOM) (m) | Depth of crater WOM (m) | Crater radius with magnet (WM) (m) | Depth of crater WM (m) |
|-----|-------------|-------------|-----------|----------------------------------------|-------------------------|-------------------------------------|-----------------------|
| 1   | 40          | 20          | 30        | 6.62E-05                               | 3.97E-05                | 4.44E-05                            | 4.30E-05              |
| 2   | 40          | 30          | 50        | 9.17E-05                               | 4.97E-05                | 6.14E-05                            | 5.96E-05              |
| 3   | 40          | 40          | 100       | 1.37E-04                               | 5.96E-05                | 1.02E-04                            | 6.95E-05              |
| 4   | 40          | 50          | 180       | 1.85E-04                               | 7.94E-05                | 1.61E-04                            | 8.94E-05              |
| 5   | 40          | 60          | 250       | 3.23E-04                               | 8.94E-05                | 1.07E-04                            | 9.93E-05              |
| 6   | 40          | 70          | 450       | 2.94E-04                               | 1.09E-04                | 2.85E-04                            | 1.19E-04              |
| 7   | 60          | 50          | 180       | 2.08E-04                               | 8.94E-05                | 1.69E-04                            | 9.93E-05              |
| 8   | 60          | 50          | 180       | 2.08E-04                               | 8.94E-05                | 1.34E-04                            | 1.09E-04              |
| 9   | 60          | 50          | 180       | 2.08E-04                               | 8.94E-05                | 1.22E-04                            | 1.19E-04              |
| 10  | 80          | 50          | 180       | 2.16E-04                               | 9.93E-05                | 1.76E-04                            | 1.09E-04              |
In Fig. 4 shows the single spark result. In Wire-EDM the spark is generated between the cathode and anode electrode and it should maintain a gap of 9-15 micrometer. The total operation is set inside the dielectric medium to protect it from a short circuit and also to help in removing debris. The work piece is kept at ambient temperature (298K). When the plasma channel touches the work piece, it starts spreading in a radial direction on the surface of the work piece (anode). The plasma channel contains the extreme heat. It affects the work piece in the form temperature distribution and formation of a crater in terms of radius and depth. The assumptions had been made, such as work piece is axi-symmetric in nature, and spark radius is in Gaussian distribution form. As shown in Fig. 1, the boundary condition is applied. After solving in ANSYS18.1, the nodal results are obtained as shown in Fig 4. It shows the transient temperature distributed and shape of the crater. In this process the microscopic particles collision happened within the work piece helps to transverse the thermal energy and those elements which are above the melting point of the material (1938k). It will be melted and evaporated. While in ANSYS those elements are eliminated because the whole work piece is divided into elements.
Figure 5. Temperature distribution and shape of crater with magnetic field $V(40)$, $i(60)$, $t_{on} = 250\mu S$ $t_{off} = 5\mu S$, $b=0.1T$.

In Fig. 5 shows that the changes appeared in the transient temperature distribution and shape of the crater when the magnetic field is applied to the spark with the same parameter such as voltage (40V), current (60A), $t_{on}$ (100ms). While comparing the Fig. 4 and Fig. 5. It clearly shows that the radius of the crater has reduced and depth has increased. Because the external electromagnet the more electrons reach into the work piece due to this the more amount heat enters into the work piece. And also the addition Lorenz force act at the centre which makes to confine the radius of the spark. The particles in the plasma channel move in the cycloid path and area of spark reduces, the pressure increase due to which the depth increases as shown in the Fig.5.
In Fig. 6c, shows that as the current increases the radius of spark also increases due to the number of electrons produced in the second is increased. The magnetic and non-magnetic both are having an electrostatic repulsive force and self-magnetic but when external electromagnetic applied to the spark addition magnetic field helps to confine the plasma channel. It helps to stop spread in a radial direction. To confine this force, magnetic field (b=0.1T) is applied on the spark. As shown in Fig. 6e the radius of spark is smaller when compared with the non-magnetic. It helps to increase accuracy in a machining operation.

In Fig. 6c, and Fig. 6g, shows that as t_{on}(time) increases the radius and diameter of spark also increases. This is happened due to more discharge time (collision of electrons that take place in plasma channel).

In Fig. 6a show that as the current (i) increases, the depth also increases due to the more electrons are able to reach the surface of the work piece. However, the increase in depth due to a magnetic field is higher compared with non-magnetic WEDM.

In Fig. 6b shows that the voltage increases the crater depth also increase due to the increase in discharge energy.

In Fig. 6f shows that under the effect of magnetic field, a voltage (V) increases from 40 to 80 V, the crater radius is reduced compared with non-magnetic field due to the drift velocity of
electrons increases which make reduction in electrostatic repulsive force and time taken by electron to travel between electrode

- In Fig. 6d shows that the depth of crater increases, as magnet(T)increase from 0.1 to 0.3 due to the increase in discharge energy

- In Fig. 6h shows that the radius of crater decrease as magnet(T)increase from 0.1 to 0.3 due to external electromagnetic applied to the spark addition magnetic field helps to confine the electrostatic repulsive force.

5. Conclusion

In this work, numerical investigation of wire-EDM process under magnetic field has been performed. And following conclusions can be drawn:

- The positive things about using a magnetic field on the spark in WEDM Method were understood at a basic level using single-discharge in numerical modeling. In WEDM, the magnetic field assistance reduced crater diameter and increased the depth. These results were verified by FEM based electro thermal model was solved by using the ANSYS18.1 software for forecast the cause of Lorentz forces on the crater in terms of diameter and depth.

- Due to the external electromagnetic force were acted on the electrostatic repulsive force which helps to confine the plasma channel in the radial direction and more discharge energy is developed.

- Under electromagnetic field the crater radius has decreased and the depth has increased.

6. References

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