MACHINING ATTRIBUTES OF ELECTRICAL DISCHARGE MACHINING – AN ASSESSMENT

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ABSTRACT:

The machining attributes of the procedure in an electrical discharge machining (EDM) directly rely on the discharge energy that is changed into heat in the area where machining takes place. High temperatures are the outcome of the thermal energy that is generated which lead to local melting and evaporation of the workpiece material. On the other hand, the different physical and chemical attributes of the tool and workpiece are influenced by the high temperature. Depending on the earlier studies, an investigative reliance was set amongst the criteria of discharge energy and technological performance. Furthermore, attributes of discharge energy was experimentally analysed and their impact on productivity preciseness and EDM quality was set. The mathematical and investigational studies undertaken in the current study permit growth of intelligent modelling methods for successful choice of pertinent criteria of EDM discharge energy. The outcomes got symbolise a technological basis for the choice of ideal settings of EDM procedures.

Key words: EDM, machining parameters, technological performance, modeling, optimization

1. OUTLINE

Contemporary production has to deal with intricate requirements on a day to day basis. Production adaptability, output and quality are the major crucial requirements that the market oriented industrial systems have to handle. It is merely the contemporary equipped industrial systems that can successfully adapt their production procedures to such high market requirements. In this reference, there can be limited uncertainty that the machining
procedures shall stay to be a crucial integral aspect of the technological procedure of goods production and assembly. The fundamental benefits of machining procedures include high technological performance (effectiveness, accuracy and quality) with the skill to handle the hard materials and intricate surfaces [1-4]. Depending on the present investigation and likely forecasts, one can anticipate enhanced use of electrical discharge machining (EDM) in contrast to other present traditional and non-traditional machining procedures [5-7]. EDM is one of the most crucial non-traditional machining procedures employed for intricate machining of several varied segments of electrically conductive materials, irrespective of their physical and metallurgical attributes [8]. As is evident, there are several advantages of EDM. It is generally suitable to employ EDM in contrast to traditional machining procedures; however, this may not be the case always as the EDM has specific technological limitations. EDM procedures comprise of machining of materials that provide at least 0.01 S/cm of electrical conductivity [9]. In contrast to traditional machining, output is comparatively reduced. The preciseness of the machined aspects is impacted by the tool wear and tear. The machining preciseness of the EDM is restricted to around ±0.001 mm. The least surface roughness mean is approximately 0.1 μm. EDM encourages thermal stress in machined surfaces. Surface integrity can be as good as or superior to a ground surface [10,11].

2. BASICS OF ELECTRICAL DISCHARGE MACHINING
The roots of electric discharge machining can be dated way back to 1770 after J. Priestly identified the impact of electrical discharges. B. Lazarenko and N. Lazarenko in 1943, had introduced the controlled EDM procedure for machining materials. The emergence of EDM post 1970 was on account of numerical control, strong generators, new wire tool electrodes, enhanced machine intelligence and superior technological facets. Off late, the inclusion of EDM in a computer integrated production lead to a crucial lowering in machining outlays and competitiveness. The EDM is primarily an intricate procedure which relies on periodical chance of electrical energy into thermal energy [12-14]. Thermoelectric energy is developed amongst the tool and workpiece when the electric current is passed through. Both the workpiece electrode materials and the tool needs to be conductors of electricity.
and dipped in a dielectric fluid. A particularly small distance is kept amongst the tool and the workpiece. The timing and intensity of the electrical discharges and the movement of the tool in association to the workpiece is controlled by a power supply. Fig. 1 shows the diagrammatic representation of the primary working principle of EDM, input procedure criteria (workpiece, tool, machine and dielectric) and output technological performances (outcomes, machining preciseness and surface integrity).

2.1 Working principle of EDM process
The working belief of EDM procedure relies on a sequence of non-stationary electrical discharge which eliminates material from a workpiece [15,16]. Material elimination rate takes place at the position wherein the electric field is most robust. On starting the voltage, a robust magnetic field is set amongst the tool and workpiece (ignition stage). On account of the alluring force of the magnetic field, at the shortest local distance amongst the tool and workpiece there is collection of particles from the machining procedures which float in the dielectric liquid. This gives rise to the electrical circuit and the electrons start shifting to the positively charged electrode. On their way, the fast moving electrons clash with the neutral particles from the machining procedures and dielectric liquid. There is a chain response under which several negative and positive ions are produced (discharge stage). The ionization begins development of an electro-conductive zone amongst the workpiece and tool, thereby resulting in electrical discharge. In electrical discharge, electrical energy is changed into thermal energy. A discharge zone is shaped at temperatures that can reach 40,000 °C. Such high temperatures result in local heating, melting, evaporation, and burning of workpiece material. High temperatures also generate inferior machining quality, lead to wear and tear of tools, thermal dilatations, and the like. The interruption of supply of current destroys the discharge zone, leading to sudden cooling which leads to a volatile cleansing of melted matter and solid particles off the surface of the workpiece (ejection stage). Fig. 2 represents a single electrical discharge of
the EDM procedure with electrical pulse criteria [17,18].

Amongst the periodical discharges there is the presence of deionization of dielectric liquid and the products of machining are removed from the work zone. This procedure offers constancy of pulse discharge by evading the consistent current flow and generation of electric arc or a short circuit. There exist voltage and current pulses during the electrical discharge which differ in time (Fig. 2). Electrical pulse are co-dependent, and are ascertained by the subsequent criteria: $U_e$ – discharge voltage, $I_e$ – discharge current, $t_e$ – discharge duration, $t_o$ – pulse off time and $t_p$ – pulse cycle time. The derived criteria include: $E_e = U_e I_e t_e$ – discharge energy, $f = 1/t_p$ – pulse frequency and $\tau = t_e/t_p$ – duty factor. The discharge energy is the most crucial criterion of EDM. The discharge energy is the average value of electric criterion which is changed into heat during discharge. It is directly impacted by the attributes of electric pulses. Their impacts are correlated and rely on the remainder of the machining criteria [19,20]. The discharge voltage relies on the combined electrode materials and machining settings. It varies from 15 to 30 V [21]. For suitable machining settings, electrical discharge takes place instantly and is neutral from other electrical pulse criteria. Thus, the most significant pulse criteria of EDM include discharge current and duration of the discharge. On the other hand, the influence of discharge current is restricted by the tool surface that interfaces the workpiece, i.e. the current density [22,23]. In the event wherein the current density surpasses the restriction for the decided machining settings, the procedure of deionization of the discharge zone declines, thereby lowering the EDM efficacy. The unbiased norm of the duration of the discharge if also restricted. Experience proves that the duration of discharge needs to remain restricted for a specific discharge current. Else, an electrical arcing takes place which harms both the tool and workpiece. Additionally, apart from the electric criteria enumerated previously the polarity ($\pm$) of electrodes has a crucial influence on the EDM outcomes. The polarity can be positive or negative and it relies on tool material, workpiece material, current density and duration of the
discharge. Since the plasma channel is created from ion and electron flows, and electrons have mass smaller than anions, for that cause electrode polarity is generally positive, permitting achievement of a suitable material elimination rate and the least comparative tool wear proportion [24,25].

2.2 Machining attributes

Akin to other machining procedures, the most significant EDM machining attributes include the following: output, machining preciseness and surface reliability (Fig. 1). Output is articulated to be the material elimination rate and indicates how quickly the workpiece material is removed per unit of time. Machining preciseness is described by acceptability of dimension and form of the workpiece. Surface integrity is articulated via surface roughness and surface layer attributes. The significance of machining performance is comparative and relies on machining settings and the anticipated operations of the parts. In addition to the machining outlays, output ascertains the general cost-effectiveness of the machining procedure while preciseness and quality influences the operational worth of the product. The material eradication procedure in EDM is linked with the erosive impacts which take place on account of a very high temperature on account of high intensity of discharge energy via the plasma channel (Fig. 2). The material elimination rate and the surface integrity are equivalent to the modified crater profile that is described via the radius. The crater radius is presumed to be an operation of discharge energy [17,26,27]. Thus, one can rationally presume that the material eradicated volume of a single electric pulse would be relative to the discharge energy:

\[ V = C_V \cdot E \]  

here \( C_V \) symbolises the constant that relies on the workpiece material. The material removal rate stands for the mean volume of material removed over the machining time and there follows the term for material removal rate:

\[ V_w = V_e \cdot f = C_P \cdot U_e \cdot I_e \frac{t_e}{t_e + t_0} \]  

However, the material removal in a single pulse discharge is ascertained by calculating the crater volume, using the presumption of hemispherical shape whose radius is equivalent to \( R_{max} \):

\[ V_e = \frac{2}{3} \pi R_{max}^3 \]
In Eq (3), $R_{max}$ is described to be the optimal surface roughness noticed over optimal height of inequalities. By employing both Eq. (1) and from Eq. (3) one derives the term for optimal height of irregularities:

$$R_{max} = \left( \frac{3}{2\pi} C_T E_g \right)^{1/3}$$

(4)

In reality, the surface quality is described over the surface roughness $Ra=R_{max}/4$. The surface roughness is described to be the mathematical mean deviation of the investigated profile (ISO 4287). Academically, reliance of the gap distance and the discharge energy is given by equation:

$$a_g = C_a E_g^M$$

(5)

2.3 Varied Kinds of EDM

EDM system can be segregated into two fundamental kinds (Fig. 3): Die-sinking and wire-cut. Die-sinking EDM, also referred to as Ram EDM or standard EDM is the oldest kind of EDM machining. The wire-cut EDM, also referred to as WEDM or spark EDM, is controlled by CNC following the allocated geometry for the part to be manufactured [5-7, 28, 29].

Die-sinking EDM replicates the tool form into the tool or the fabric. Die-sinking EDM are commonly utilised for intricate geometries where the machine a graphite shaped or copper electrode is employed. Several die-sinking EDM machines that have CNC control have the capacity to turn the electrodes around more axis permitting machining of intrinsic hollows. This allows die-sinking EDM to become an extremely skilled production procedure. In wire-cut EDM a wire electrode is employed to cut a programmed shape into the workpiece. Wire-cut EDM is employed for outlines cut-outs from a flat sheet or plate. With a wire-cut EDM machine, a starting hollow needs to initially be drilled through the material after which the wire can be fed through that hollow to finish the machining assembly. The wire-cut EDM can generate all types of complex outlines that are extremely tough with other procedures.

2.4 EDM FUNCTIONS
EDM presently is a crucial procedure in the contemporary production sector. The employment of EDM is crucial for machining tough to-machine materials (toughened alloy steel, high speed steel, superalloy, cemented carbide) and intricate geometry facets for which conventional methods cannot be used [1, 5]. It is chiefly employed for the manufacturing of delicate hollows in making tools or polymer injection, modern parts or other extremely unique goods. With the enhanced ability of EDM controls, novel procedures employ simple-shaped electrodes to 3D EDM intricate forms. As the tool fails to get in contact with the workpiece cutting forces are absent, thus, very delicate parts can be machined by EDM 30,31. Furthermore, there is immense significance to EDM on the manufacture of extremely precise small and micro parts. Fig. 4 shows few of the uses made by the EDM procedures.

3. INVESTIGATIONAL TECHNIQUE
As evaluated in segment 2.2, the machining attributes of EDM majorly rely on the discharge energy, i.e. discharge current and duration time [32-34]. The Fig. 5 indicates the impact of the majorly crucial electrical pulse criteria on the material removal rate of tool employing the copper tool electrode. The diagram indicates the reliance of material removal rate on the length of the discharge for different discharge currents. The outcomes of investigational analysis indicate that for every discharge current there is an equivalent best discharge duration $te(opt)$ that permits optimal material removal rate. This value rises with the rise of discharge current [13,21]. This successfully prevents us from unmistakable ascertainment of the impact of the discharge current and pulse duration on material removal rate. The investigated set maximum impact of the electrical pulse criteria on material removal rate disagrees with the anticipated impact. In actual settings, the material removal rate rises with discharge current and discharge removal in addition to the rise of gas bubbles in the discharge zone. On account of the reduced removal of machining goods, a share of the discharge energy is consumed on remelting and evaporation of hardened metal particles. Furthermore, a bigger segment of the discharge energy occurs in a gaseous setting, thereby being lost forever. Such reduced procedure constancy impacts the efficiency of EDM.
Fig. 6 indicates the impact of discharge current and length of duration on the gap distance. The diagram indicates that the rise of electrical pulse criteria leads to a rise in the gap distance [13, 21]. Despite the impact of discharge current and discharge duration on gap distance is the same; the discharge current has a rather bigger impact on the gap distance. It is clear that the gap distance trails the electrical pulse criteria so as to sustain constancy of EDM. Then, the deionization of the discharge zone would be impacted, which could lead to either low or unrestrained material removal rate.

Fig. 7 shows the association amongst the surface roughness and electrical pulse criteria. The outcome of the investigated analysis indicates a limited rise of surface roughness with the rise in the time length of the duration; at the same time, the discharged current appears to have a distinct impact on the surface roughness. As there is a rise in the discharge current, the discharge heat concentration on the workpiece surface also rises, which leads to huge craters, i.e. a rise in the surface roughness. The fig. 7 shows the characteristics images of machined surfaces at different electrical pulse criteria. The EDM surface comprises of several craters of different measurements, while the roughness is same across all directions [13,21].
As EDM results in very high temperatures in the machining area, the workpiece surface layer is anticipated to have thermal flaws. Fig. 8 shows the metallographic image of the surface layer of tempered tool steel, which was corroded by a copper tool with a specific criteria related to discharge energy.

According to the metallographic analysis it was indicated that there was a transition in the surface layer of the workpiece. The modifications are seen as unequal thickness, microstructure changes, and an altered microhardness in contrast to the earlier condition of workpiece material. In Fig. 9, one can witness the reliance of recast layer thickness on the discharge energy [18, 35-37]. An evaluation of the metallographic images show four typical secondary-changed workpiece surface layers: melted metal layer, hardened layer, interface layer, and tempered layer. The melted layer refers to a slush of lightly welded particles which actually are the scum remaining post the elimination of melted material from the crater. The hardened layer includes martensite, remainder austenite with exceptionally distinct grains, and cementite. The interface layer comprises of martensitic-austenitic grid, and cementite, where the proportion of austenite reduces with the distance from the tempered layer.

The microstructure of the tempered layer is hardened martensite, and cementite, martensite, and cementite, which slowly changes into fundamental microstructure which is made up of martensite with fine globular cementite.
In contrast to the earlier condition of the material, the tempered layer has lower microhardness while the secondary-hardened layer has higher microhardness [Fig. 8]. The lower microhardness of the tempered layer takes place around the highly tempered grains in the martensitic-austenitic grid while the higher microhardness of the hardened layer is on account of the austenitic-martensitic phase change.

4. MATHEMATICAL PROTOTYPE OF EDM

The mathematical modeling of the EDM procedure relying on the electro-thermal prototype is undertaken employing the investigational-numerical processes. It is a known fact that the thermal modeling of EDM procedures is extremely tough. The function of modelling post the thermal occurrence in the EDM is to use the most suitable mathematical prototype of aspects in the discharge zone and their associations [38-40]. For defined thermal prototype of EDM, the partial differential equation of heat conduction in two dimensional cylindrical coordinate system for the workpiece and tool can be regarded to be as expressed subsequently:

\[ \rho c \frac{\partial T}{\partial t} = k \left( \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} \right) \]  \hspace{1cm} (6)

The Differential Eq. (6) needs to be taken in concurrence with the earlier temperature that can be considered should be considered to be the normal room temperature of the dielectric in which the researcher completely immerses the electrodes:

\[ T(r, z, t) \big|_{t=0} = T_0 \]  \hspace{1cm} (7)

and the boundary conditions of the system:

\[ -k \frac{\partial T(r, z, t)}{\partial z} \big|_{z=0} = q(r, t) \]  \hspace{1cm} (8)

\[ -k \frac{\partial T(r, z, t)}{\partial z} \big|_{z=\infty} = 0 \]

\[ -k \frac{\partial T(r, z, t)}{\partial r} \big|_{r=\infty} = 0 \]

where \( T \) stands for the temperature, the radical cylindrical coordinate is represented by \( r \); the axial cylindrical coordinate is shown by \( z \); time is represented by \( t \) while thermal conductivity is \( k \), \( \Box \) is the material density, the specific heat is \( c \) and \( q \) is the heat flux density. The finite element method (FEM) that is employed to resolve partial differential equations of heat conduction (Eq. 6) employing the
Galerkin’s method can be articulated in matrix form as shown under:

$$[k][T] + [c] \frac{\partial T}{\partial t} = \{q\}$$  \hspace{1cm} (9)

Where thermal conductivity matrix is $[k]$; the specific heat matrix is $[c]$; the temperature vector is $\{T\}$ and the heat flux vector is $\{q\}$ [41-43]. The Fig. 10 indicates an instance of 3D axisymmetric finite element prototype of the EDM electrical pulse discharge procedure.

As indicated in Fig. 11, the outcomes of FEM modelling of the volume of material removed were contrasted with the investigational outcomes. The diagram indicated that the rise in discharge energy, leads to enhanced radius and depth of the crater, which finally results in higher volume of material eliminated from the workpiece. The mean volume of material eliminated from the workpiece is gauged employing numerical approximated value geometry of the crater.

**5. MODELING OF EDM PROCEDURE EMPLOYING ARTIFICIAL INTELLIGENCE**

Off late, few studies conducted in the beginning evaluated the fundamental artificial intelligence method to design the machining procedures; these have been comprehended. To generalize the investigative outcomes and create the system prototype precisely, neural networks, fuzzy systems, evolutionary computation and the like are considered to a substitute method. The review of literature makes it evident that artificial intelligence methods have been comprehensively employed in the modelling of procedure criteria in addition to controlling the EDM system [44-47]. As recommended by the names, the evolutionary algorithms rely on values of growth and natural choice. Every response to the issue is regarded to be a distinct one.
that is assessed by the fitness operation. The outcomes of the assessment directly ascertain every person’s likelihood of mating and thereby shifting his genetic matter to the subsequent generation [48-50]. The evolutionary algorithms are a bigger set of algorithms depending on evolution but frequently merely genetic algorithms (GA) and genetic programming (GP) are characterised. Both of these algorithms are driven by character in the same manner: they use evolutionary attributes of choice, crossover and mutation on resolving issues while paying heed to the law of evolution, survival of the fittest, slowly moves to the most suitable response. In genetic algorithms, outcomes are people while solutions in genetic programming are entire computer programs. Instance for a prototype of the genetic algorithms for material removal rate $V_w$, gap distance $a$ and surface roughness $Ra$, based on the discharge currents $I_e$ and discharge duration $t_e$, are represented by the subsequent equations:

$$V_w = 0.86 \cdot I_e^{0.9} \cdot t_e^{0.202}$$
$$a = 0.054 \cdot I_e^{2.4} \cdot t_e^{0.054}$$
$$Ra = 2.125 \cdot I_e^{0.468} \cdot t_e^{0.041}$$

The subsequent text discusses the advancement and usage of an ANFIS (adaptive neuro-fuzzy inference system) in electrical discharge machining for envisaging the surface roughness. In the present ANFIS system, discharge current and discharge length are the input variables while surface roughness is the output as indicated in Fig. 12. The recommended ANFIS prototype in the current research offers an accurate and effortless choice of EDM input criteria and results in a superior machining settings and reduces the machining outlays [52,55].

Fig. 12. ANFIS modeling of surface roughness in EDM process [55]

The ANFIS modeling of EDM could successfully envisage the investigational outcomes and have indicated the forecasts on the surface roughness with a limited mean flaw. ANFIS provides the mapping association amongst the input and output data by employing the hybrid learning technique to ascertain the best distribution of membership operations [53]. The ANFIS architecture employs both the artificial neural network (ANN) and fuzzy logic (FL) [54]. The contrast of investigational ANFIS ANN and GP envisaged outcomes for the surface
roughness are explained in Fig. 13. It validated that the techniques employed in the current study are viable and could be employed to envisage the surface roughness in a suitable error rate for EDM. The contrasted lines appear to be close to one another showing suitable conformity. The contrasted reflections indicated that the genetic algorithms provide a limited smaller deviation of the calculated values of prototype compared to the neuro-fuzzy prototype [51,55,56].

6. FUNCTION FOR CHOOSING EDM CRITERIA

Depending on the synopsis of inferences drawn from the investigational analysis [13, 18, 21, 57], it was identified that the prototype for choosing the maximum electrical pulses criteria in EDM. The Fig. 14 indicates the mutual reliance of material removal rate, tool wear ratio, gap distance and surface roughness for maximum electrical pulse criteria. The chosen tool surface or surface roughness allows to select discharge current and pulse length which leads to optimal material removal rate, and the equivalent gap space and tool wear and tear proportion.

![Fig. 14. Model for selection of the optimal electrical pulse parameters in EDM [21]](image)

The application form for automatic choice of input criteria in electrical discharge machining is shown in the Fig. 15.

![Fig. 15. Application for selection of EDM parameters](image)

5. INFERENCES

Depending on the literature review, it was comprehended that the electrical discharge machining (EDM) is a normal kind of machining in production sector. Thus, the machining attributes of EDM chiefly rely on creation and distribution of discharge
energy in the machining zone. The energy created relies on the discharge current and time of duration, while the energy distribution relies on the physical and chemical attributes of the discharge zone. As the EDM procedure is intricate and stochastic in character, majority of the endeavours to shape the technological performance of EDM procedures in literature has been stated to rely on electrothermal notions. Thus, for the modelling of EDM the investigational, mathematical, experimental or intelligent techniques are employed, with varied attributes and estimated outcomes. The undertaken hypothetical method and experimental analysis of the machining attributes of EDM lead to the subsequent inferences:

- Technological performance of EDM directly relies on the discharge energy which changes into thermal energy in the discharge zone;
- The presence of suitable discharge energy which gives best productivity and machining quality;
- The investigative-numerical modelling of EDM is a realistic manner to dependably ascertain the method of production and distribution of thermal energy in the discharge zone and also envisage the material removal rate and surface roughness;
- Analysis indicated that intelligent prototypes provide precise estimate on technological performance in EDM;
- Values envisaged by the mathematical and intelligent prototype generally concur with the investigational outcomes and the variation amongst the modelling and investigational outcomes are chiefly on account of the issues to include all impacts in the electrothermal prototype of EDM procedure.