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ScienceDirect

Procedia Manufacturing 26 (2018) 1471–1482

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

46th SME North American Manufacturing Research Conference, NAMRC 46, Texas, USA

Investigation on non-invasive process monitoring of Die Sinking EDM using Acoustic Emission signals

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Abstract

Die sinking electrical discharge machining is used extensively to produce very complex geometries on difficult-to-machine materials for aerospace, automotive, mold and die applications. The quality of the component produced mainly depends on the quality and intensity of spark generated between the tool and the workpiece. The present research work focused on using the acoustic emission signals to characterize the spark activity in the EDM process under different machining conditions. Experiments were conducted by varying the machining conditions and using three tool electrode materials namely graphite, copper and copper tungsten. The acoustic emission signal features were extracted from the data collected from different experimental conditions and are related to the various parameters including current, voltage, pulse on-time, surface roughness parameters (Ra and Rq) of the workpiece and material removal rate (MRR). The effect of tool material on the AE phenomenon was also investigated. The process conditions were found to have to have a good correlation with the acoustic emission signals features. Multiple linear regression models were built to predict the surface roughness (Ra) of the workpiece and MRR using only the current and pulse on-time as predictor variables. The prediction accuracy of the models improved by the addition of AE signal features to the predictor variable set. The results obtained indicate a suitability of employing acoustic emission signals for monitoring the spark activity, MRR and surface finish of the workpiece in the EDM process. Based on this, a reliable monitoring and diagnosis tool for EDM can be developed using the AE sensor and provides an opportunity to implement the industry 4.0 initiatives effectively.

Keywords: Die sinking electrical discharge machining; Acoustic Emission (AEs); Process monitoring; Surface roughness parameters; Material removal rate (MRR)

1. Introduction

Electrical Discharge Machining (EDM) is a non-conventional machining process. In EDM, electrical energy is utilized to generate an electric spark between the tool and the workpiece. The material removal mainly occurs due to the thermal energy of the spark. The unique feature of EDM lies in its ability to

10.1016/j.promfg.2018.07.094

machine materials irrespective of their hardness and strength. Work material used in EDM has to be electrically conductive. In EDM, precise control of the spark activity is crucial as it has a great impact on the performance parameters namely material removal rate (MRR), tool wear and the surface finish. Thus a reliable sensing strategy and process monitoring technique are required to monitor and control these performance parameters. In EDM, discharges take place by the flow of current from the tool electrode to the workpiece (or in the reverse direction).The gap current and the voltage carries important information about the process. Hence current and voltage waveforms are used widely for real-time monitoring of the EDM process. 'Shunt resistor 'and 'Current probes with Hall sensor' are used conventionally to acquire the current waveforms in the EDM process [1]. A conventional high-impedance probe is commonly used along with an oscilloscope for gap voltage measurement [1].Current and voltage waveforms are used to discriminate sparking, arcing, short and open circuiting occurring in the EDM process [2]. Radio signals are also used for monitoring of the EDM process. Bhattacharyya et al. [3] measured the radio signals emitted during the process using a normal radio receiver and a wire antenna and reported on the feasibility of using radio signals for process monitoring of EDM. The radio frequency waves were able to detect the process anomalies that cause process instability such as arcing, short-circuiting but cannot be used to continuously monitor the MRR and surface roughness (Ra) as they showed very little variations for a considerable change in EDM parameters such as current and pulse on-time at different process conditions.

The application of Acoustic Emission (AE) in EDM is an emerging technique.AE is found to have a good potential to reveal salient information about the EDM process phenomenon.AE basically refers to transient elastic waves generated from the rapid release of energy in the material [12]. The source of AE waves can be from initiation and growth of cracks in materials, atomic dislocation, phase transformations in metals, melting or solidification, etc. Acoustic emission sensors have been used in process monitoring of conventional machining processes such as turning, milling and grinding [4]. AE sensors have proven to be a powerful diagnostic tool in areas other than machining. AE sensors have been used to detect partial discharges in power transformers. An attempt was made by Cichon et al. [5] to study partial discharges using three different types of spark gap configurations: point-point, point-plane, and surface. The AE Signals were analyzed using Short Time Fourier Transform (STFT) and wavelets. It was demonstrated that partial discharges that occur from each of the spark gap configuration can be assigned a possible frequency band. The relationship between the discharge energy and the AE signals in micro-EDM of Polycrystalline diamond (PCD) was studied by Mahardika et al. [6] and it was found that the peak amplitude of the AE signals was proportional to the discharge energy. As this discharge energy increases, the acoustic emission activity increases giving rise to an increase in the fracture energy detected by the sensor. The elastic waves (AE waves) are also reflected and transmitted by the various components of the machine [6].AE signals are also used to monitor process instabilities such as the adhesion (molten part of the workpiece getting attached with the tool material causing short-circuit) at the inter-electrode gap and can be subsequently used for online monitoring of the tool electrode wear [7].The concept of using AE to locate discharges was first proposed about 20 years ago but the overlapping of AE wave and electromagnetic interference (EMI) in case of a single discharge and overlapping of AE waves from two successive discharges in case of sequential discharge have restricted its development. Craig Smith et al. [8] addressed this difficulty by analyzing the AE signal in the frequency domain using Fourier transform. This frequency spectrum analysis was able to clearly differentiate the AE signals from the EMI noise. Short Time Fourier Transform (STFT) was also performed to obtain the spectrogram of the AE signal. The acoustic emission time lag in wire EDM was also determined by analyzing the spectrogram of the AE signal for two wire types namely brass and zinc coated brass. Based on this, a method was also proposed to identify the length of the electrode wire and height of the workpiece in fast-hole and wire EDM [8]. Alexander Goodlet et al. [9] reported on the application of AE for monitoring and quantifying the flushing in the inter-electrode gap. AE signals are found to complement the current and the voltage waveforms as they enclose numerous valuable information related to the efficacy of the material removal. AE RMS values obtained were found to correlate well with MRR values for different levels of flushing and thereby serve as a useful indicator for determining the optimal flushing conditions. The influence of the dielectric medium on the acoustic emission activity was also investigated in this study. AE signal was acquired with the inter-electrode gap filled with dielectric oil and in dry condition. AE bursts were discernible when the gap was filled with dielectric liquid whereas AE signal obtained for dry condition was very weak. This suggests that the component of acoustic emission activity from the gas bubbles (emerging in the vicinity of the plasma channel due to the vaporization of the dielectric liquid) is significant than the one arising from the plasma channel [10]. In a recent work [10] the acoustic emission measured in EDM was interpreted by measuring the forces occurring during the discharge process and the dynamics of gas bubbles at the tool-workpiece interface. The possible sources of AE in EDM are (i) the plasma channel, (ii) the gas bubble that originates in the surrounding area very close to the plasma channel due to vaporization of the dielectric and (iii) the shock waves originating from the gas bubble dynamics (comprising of formation, rapid expansion, collapse and rebound of gas bubbles) in the inter-electrode gap [10].The influence of various dielectric liquids on the acoustic emission activity was also investigated. AE signals were acquired when using two different dielectric media namely deionized water and oil. AE RMS value obtained when using deionized water was relatively higher. This observation was attributed to the kinematic viscosity of water which is less than that of the dielectric oil. Due to its lower kinematic viscosity, the expansion of gas bubbles generated around the plasma channel after each discharge is well facilitated by the water medium than the oil giving rise to a relatively strong AE signal. Dielectric fluids with higher viscosity (in this case oil) do not easily allow the expansion of gas bubbles. As a consequence of this, the shock waves arising from the rapid expansion of the gas bubbles are less in magnitude, giving rise to a relatively weak AE signal. Consolidating the observations and results from [8],[9] and [10], it can be understood that the gas bubbles that originate in close proximity around the plasma channel due to the vaporization of the dielectric molecules and the shock waves originating from these gas bubble dynamics, travel through the dielectric medium and are reflected and transmitted by the dielectric tank.

Thus, in the present research work, an AE sensor was mounted on the front side of the dielectric tank instead of mounting it directly on the workpiece or tool electrode thus making the process monitoring technique completely non-invasive. The effect of the tool material and various EDM parameters like current, voltage and pulse on-time on the AE signal was investigated using the extracted AE signal features. The extracted time domain features of the AE signal were related to the performance parameters such as MRR and surface roughness (Ra and Rq). Multiple linear regression models were also built to predict the surface roughness (Ra) and the MRR using the AE signal features along with the machining parameters.

Nomenclature

Δm	Mass loss of the workpiece
ρ_w	Density of the workpiece
t_m	Machining time
MRR	Material removal rate
E	Discharge energy
V	Discharge voltage
I	Discharge current
T_{on}	Pulse on-time
AE	Acoustic Emission

2. Materials and Methods

Experiments were carried out on a sinker EDM machine (ELECTRONICA 5030 ZNC). EDM Oil - IPOL SEO 450 was used as the dielectric fluid. The workpiece used was similar to AISI D2 steel. Three tool electrode materials were used for the experiments namely copper, copper tungsten, and graphite. The length and diameter of the workpiece were 25mm and 8mm respectively. The density of the workpiece material was 7778 kg/m^3. The diameter of all the tool electrodes was 8mm. The Acoustic emission generated in the EDM process was sensed using an AE sensor (Model: WSα, Manufacturer: Physical Acoustics Corporation, MISTRAS Group Inc.).

Table 1. Technical Specifications of Machine Tool

Electronica 5030 ZNC Machine tool	
Work tank internal dimensions (W × D × H)	800 × 500 × 350 mm
Work table dimensions	500 × 350 mm
Traverse (X,Y,Z)	300,200,250 mm
Maximum job height above the table	250 mm

Feed motor/Servo system for Z axis	DC Servo
Dielectric system	Integral with the machine tool
Dielectric capacity	400 liters
Pulse generator	S 50 ZNC
Pulse generator type	MOSFET
Maximum working current	50A
Power supply	3 Phase, 415 V* AC, 50Hz
Connected load	6kVA

Table 2. Chemical composition of the workpiece

Elements	C	Mn	Si	Cr	V	Mo	Fe
Weight (%)	1.65	0.3	0.4	9.80	0.8	0.9	Remainder

Table 3. Tool electrode properties

Material	Nominal composition (% weight)/ Grade	Electrical resistivity (Ωm)	Melting point (˚C)	Density (kg/m^3)
Copper	99.9 % Cu	1.68×10^{-8}	1083	8904
Copper tungsten	30% Cu ,70% W	3.45×10^{-8}	3521	14180
Graphite	Grade NJ423	1.80×10^{-5}	3350	1850

The WSα sensor is a single-ended, wideband frequency, Acoustic Emission sensor [12]. The sensor was used in conjunction with a 2/4/6 preamplifier. The amplifier gain was set to 40dB so that it does not saturate the acoustic emission signal.

Table 4. AE sensor Operating specifications [12]

Dynamic characteristics	
Peak Sensitivity, Ref V/ (m/s).	55 dB
Peak Sensitivity, Ref V/µbar	-62 dB
Operating Frequency Range	100-1000 kHz
Resonant Frequency, Ref V/(m/s)	125 kHz
Resonant Frequency, Ref V/µbar	650 kHz
Directionality	+/- 1.5dB

The complete experimental setup is shown in Fig. 1. The AE sensor was mounted on the front face of the dielectric tank using a magnetic clamp as shown in the 2D schematic Fig. 2. EDM was carried out on the workpiece using copper, copper tungsten and graphite electrodes. The workpiece surface was ground before the EDM machining was performed. Negative electrode polarity (tool electrode as cathode and workpiece anode) was maintained for all the experimental runs. The pulse off-time was also kept constant throughout the experiment. Data were collected and processed using PCI-2 "2 channel AE system on a card" and the AEwin™ software. A sampling rate of 2MHz was used for collecting the AE signals. This sampling rate corresponds to a time resolution of 0.5µs. Due to the high sampling rate used the AE signals were collected only for 5 seconds at a time. A 3-D non-contact (Bruker) surface profiler was used to measure the surface roughness of the workpiece after the EDM operation. Surface roughness values were measured at three different regions on the machined workpiece surface and averaged out. 3D interactive surface profile display of the workpiece at one particular region when using copper electrode for a specific machining condition is shown in Fig. 3. The MRR (mm^3/min) was calculated using equation (1).

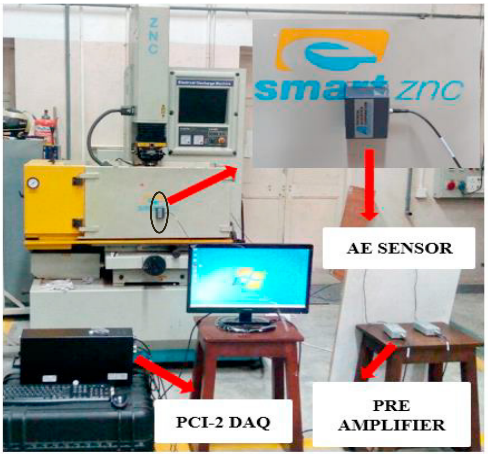

Fig. 1. Experimental setup

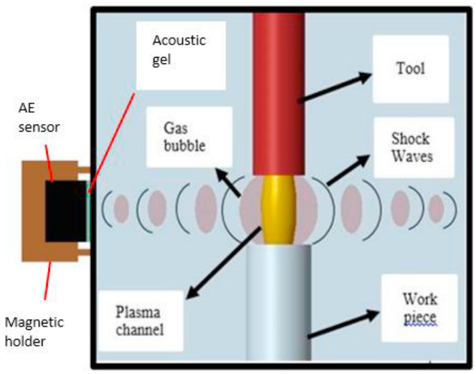

Fig. 2. Side view of the dielectric tank fitted with AE sensor

$$MRR\left(\frac{mm^3}{min}\right) = \frac{\Delta m(g)}{\rho_w(\frac{g}{mm^3}) \times t_m(min)} \qquad (1)$$

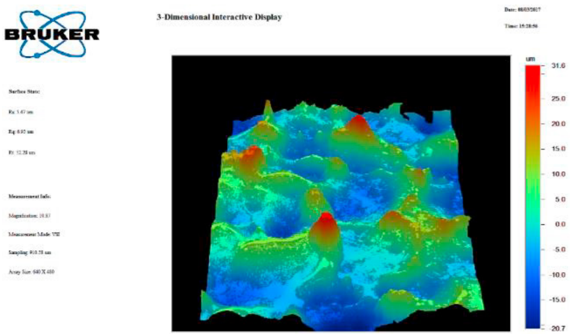

Fig. 3. 3D surface roughness Topography at I=10A, V=40V and Ton= 50µs

In an EDM process, the AE signals obtained are of burst type and not continuous. Instead of analyzing the entire time domain signal, it is logical to analyze the AE hit signal. An AE hit is detected as soon as the AE signal exceeds a threshold limit. The time domain features of the AE hits were extracted using the AEwin™ software from the collected 5 seconds duration of the raw AE signal. The time domain features extracted were

- AE RMS
- Signal strength
- Absolute energy
- AE counts

The software provides a maximum, a minimum and an average value of all the above-mentioned features. Out of these three, the average value of the features is chosen for analysis.

- AE RMS is the time-averaged value, calculated over an interval and reported in voltage [12]. As soon as an AE Hit is detected, the value of the RMS at that instant is measured and processed.
- Mathematically, signal strength is calculated by integrating the rectified voltage signal over the duration of the AE waveform [12].The physical meaning of signal strength is more intuitive as it is a representation of the acoustic emission impact energy.
- Absolute energy is calculated by the integration of the squared voltage signal and dividing it by the reference resistance (10k-ohm) over the duration of the AE waveform [12].Absolute energy (as a hit feature) is the measure of the energy contained in the AE hit.
- AE counts simply gives the count of the AE signal whenever the AE signal crosses the AE threshold [12].

3. Results and Discussions

A sample of a typical AE burst acquired during machining is shown in Fig. 4.

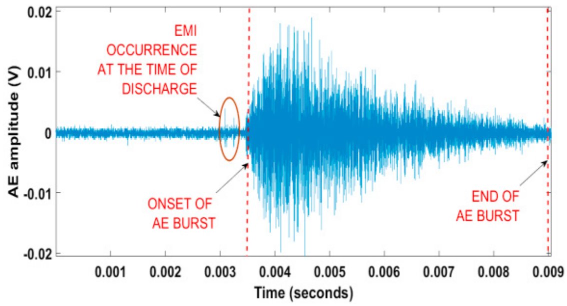

Fig 4. AE burst signal

From Fig. 4 it is observed that the AE amplitude values are very small in magnitude. This can be attributed to the fact that the AE waves get attenuated in the dielectric medium before reaching the sensor as the sensor is located on the dielectric tank at a considerable distance (255 mm) away from the discharge point.

3.1 Effect of Tool Electrode Material

As the tool material plays a crucial role in achieving a desirable MRR and surface roughness in an EDM process, the relationship between selected AE features at different machining conditions for the three tool electrodes material namely copper, graphite and copper tungsten is investigated and presented. Three experiments were performed (see Table 5) using each of the three tool electrodes. A fresh tool-workpiece combination was used for each experimental run and the dielectric was replaced with a fresh one after each experiment. The results are shown in Fig.5. (a), (b) and (c) and (d).

Table 5. Experimental conditions

Experiment	Current (A)	Voltage (V)	T_{on} (μs)
1	20	40	100
2	30	40	150
3	40	40	200

From Fig.5. (a), (b), (c) and (d), the following observations can be made.

- As the current and pulse on-time are increased together at a constant voltage, the AE RMS, signal strength, absolute energy, and the AE counts also increase irrespective of the tool material for the given experimental conditions.
- The highest values of the AE RMS, signal strength, absolute energy and AE counts are observed for a copper tungsten tool for all the experimental conditions. Thus, copper tungsten provides the strongest acoustic emission signal followed by graphite and then copper for the given experimental conditions.
- The rate of increase of the AE RMS, signal strength, absolute energy and AE count values with increase in current and pulse on-time values are almost same for copper tungsten and graphite but less for copper.

The breakdown of the dielectric and the ionization process causing discharge in EDM are directly influenced by the thermal field electron emission from the cathode (tool in this case). The amount of this thermal field electron emission directly influences the probability of discharge occurrence in the inter-electrode gap. The amount of this thermal field electron emission is characterized by a parameter called the thermal field electron emission current density. As this parameter increases, the ability of the tool electrode to cause discharge (probability of discharge occurrence) also increases. In the case of single spark discharge process, the band structure of the tool material plays a crucial role in causing the discharge. The electron work function of the tool materials affects their thermal field electron emission current density. Since the electron work function of copper (5.24 eV), copper tungsten (4.54-5.27 eV) and graphite (4.7-5.2eV) are almost similar, the thermal field electron emission current density for these three tool materials is approximately equal. So, all the three tools have the same effect on causing the discharge occurrence [14].

In the case of continuous discharges, which is relevant in this case, the most important parameters influencing the discharge occurrence are dielectric property and the temperature around the plasma channel [14]. The dielectric property is affected by the debris concentration and the nature of the dielectric and not by the tool material. But, the temperature distribution in the inter-electrode gap is affected by the thermophysical properties of the tool electrode materials. The copper tool having higher thermal conductivity (380W/ (m/K) than copper tungsten (214 W/ (m/K) and graphite (164 W/m/K), conducts the heat easily away from the discharge region. As a result, the temperature is low in the discharge region. So, the thermal field electron emission current density for copper is lower than copper tungsten and graphite [14]. Thus, under similar experimental conditions, the probability of discharge breakdown is higher for copper tungsten and graphite than copper. So, the ability to process the discharge energy and cause material removal is higher for copper tungsten and graphite giving rise to a relatively strong AE signal. Also, with copper electrodes, the phenomenon of releasing the electrons and thus initiating the ionization process and forming the spark in the gap takes place only after its own material is melted. Whereas, graphite has a high melting point and is able to emit these electrons at a much lower temperature than copper. Hence, the time taken to form the plasma (energy) channel is very less for graphite. Therefore, graphite tool initiates the spark faster and provide a high discharge energy than copper at the same experimental conditions [13].

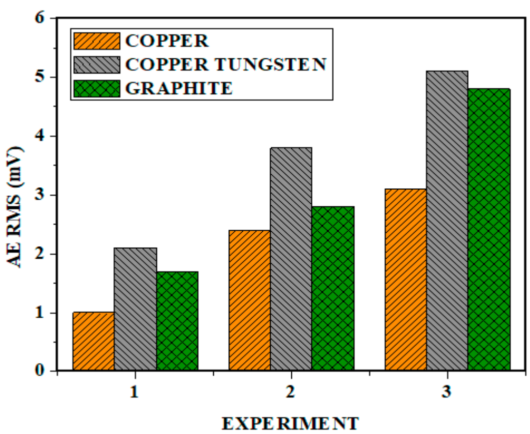

Fig. 5. (a) AE RMS comparison for copper, copper tungsten and graphite

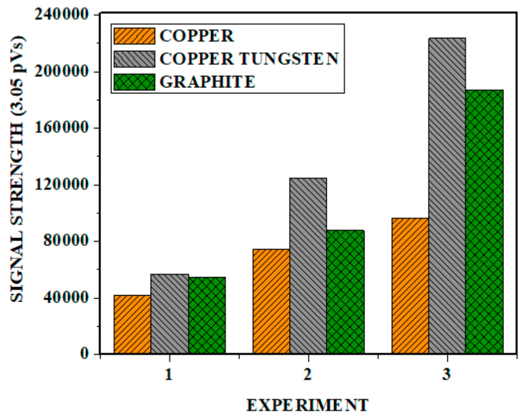

Fig. 5. (b) Signal strength comparison for copper, copper tungsten and graphite

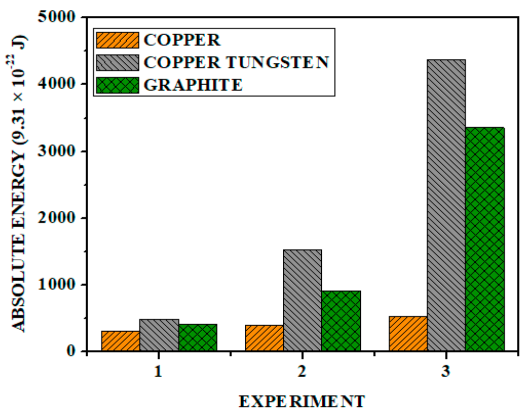

Fig. 5. (c) Absolute energy comparison for copper, copper tungsten and graphite

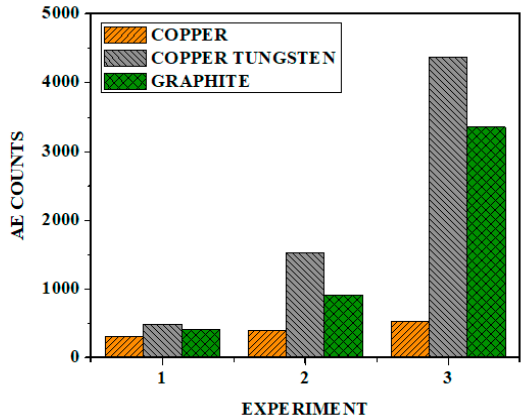

Fig. 5. (d) AE counts comparison for copper, copper tungsten and graphite

3.2 Effect of voltage and pulse on time

In an EDM process, the gap voltage has relatively less impact on MRR and the surface finish than the current and pulse on-time because gap voltage is required to only initiate the dielectric breakdown and the ionization process. At the time of sparking and material removal, the voltage in the inter-electrode gap (discharge voltage) remains fairly constant. However, in the experiments done, voltage is increased to obtain the optimum flushing conditions and to ensure that the machining instability causing the inter-electrode gap to vary doesn't affect the ionization process. Three experiments were conducted using a copper tool electrode by varying the EDM parameters as shown in Table 6. Each experiment was conducted on a new workpiece with a new copper tool electrode. The flushing conditions were same for all the experiments and a fresh dielectric was used for each experiment. The workpiece was anode and tool was cathode in all the experimental runs. The surface roughness parameters (Ra, Rq) of the workpiece and the MRR were calculated after each run and is provided along with the experimental conditions in Table 6.

Table 6. Experimental conditions

Exp. No	Current (A)	Voltage (V)	T_{on} (µs)	Ra(µm)	Rq(µm)	MRR (mm^3/min)
1	10	40	50	5.41	6.82	12.5879
2	10	80	100	6.89	8.12	17.5237
3	10	160	200	9.36	11.03	19.1309

The results are shown in Fig. 6. (a), (b) and (c).It can be seen from Fig.6 (a) that the AE RMS value increases as the gap voltage and the pulse on-time are increased simultaneously at a constant value of current. Keeping the current constant, the discharge energy increases as the pulse on-time is increased (see equation (2)). By consolidating all the observations from [8], [9] and [10] it can be understood that this increase in discharge energy causes rapid dielectric vaporization in the area surrounding the plasma channel. This gives rise to the formation of high-pressure gas bubbles in the area in close proximity to the plasma channel. Hence, the magnitude of the shock waves (pressure pulse) arising from these high-pressure gas bubbles increases. These shock waves with high magnitude travel through the dielectric medium and hit the tank surface. This phenomenon manifests as an increase in the AE RMS value of the collected signal.

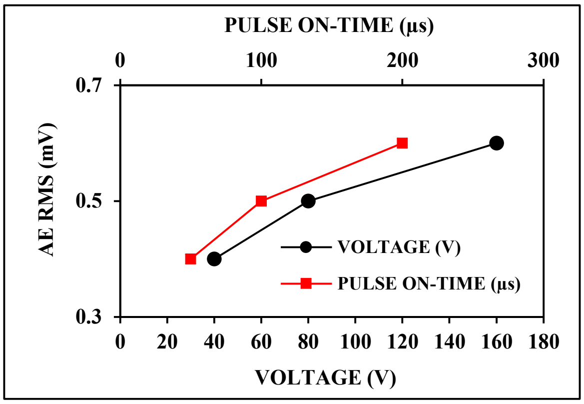

Fig. 6. (a) Comparison of AE RMS with voltage and pulse on-time

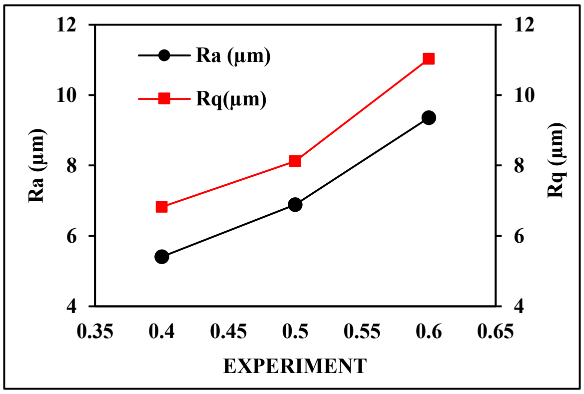

Fig. 6. (b) AE RMS vs. (Ra and Rq)

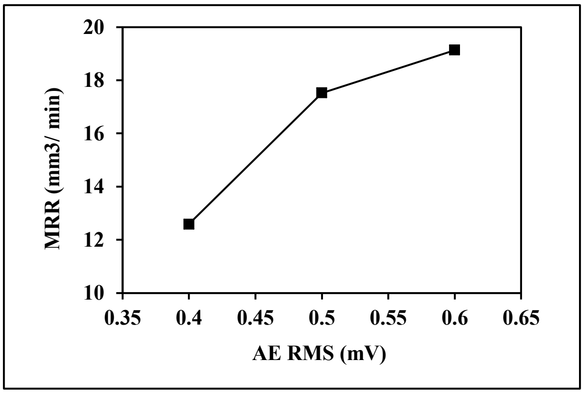

Fig. 6. (c) AE RMS vs. MRR

The comparison plots (Fig.6 (b)) between the AE RMS and the surface roughness parameters (Ra and Rq) shows that AE RMS increases with increase in surface roughness of the workpiece for the experimental conditions in Table 6. MRR also shows a similar trend with the AE RMS values (from Fig. 6. (c)).This suggests that the AE RMS proves to be a useful indicator for monitoring the surface roughness and the MRR in EDM.

3.3 Effect of current and Pulse on-time

The surface produced by EDM process is isotropic and is made up of many spherical cavities called craters. The size and depth of these craters primarily depend on the melting point of the workpieces and the discharge energy. As the discharge energy increases, the craters become larger and deeper ultimately increasing the surface roughness. The discharge energy in EDM is given by equation (2) [11].

$$E = V \times I \times T_{on} \qquad (2)$$

The discharge voltage is primarily dependent on the dielectric strength and characteristics of the dielectric fluid used and fluctuates within a small range in the inter-electrode gap. So, the discharge energy depends primarily on the current and pulse on-time. From equation (2), it can be verified that as the current and pulse on-time increases, discharge energy increases eventually causing the surface roughness to increase. Thus, it is very important to study the combined effect of current and pulse on-time on the acoustic signal by keeping the voltage constant. Three experiments were conducted using a copper electrode by varying the EDM parameters as shown in Table 7. The experimental conditions used are the same as in section 3.2.

Table 7. Experimental conditions

Exp. No	Current (A)	Voltage (V)	T_{on} (µs)	Ra(µm)	Rq(µm)	MRR (mm^3/min)
1	10	40	50	5.41	6.82	12.4839
2	20	40	100	7.67	9.53	26.0992
3	30	40	150	10.03	12.13	30.1491

The results are shown in Fig. 7. (a), (b) and (c). Comparing Fig. 6. (a) with Fig. 7. (a), it can be concluded that the AE RMS increases at a faster rate when the current and pulse on-time are increased together at a constant voltage. In section 3.2, the analysis is done by keeping the current constant and only voltage and pulse on-time were increased. The AE RMS values increased in steps of 0.1mV (see Fig.6 (a)). Here, (see Fig.7 (a)) as both current and pulse on-time are increased together, the discharge energy in EDM increases at a faster rate (verified from equation (2)) due to which the AE RMS also increases at a faster rate. Hence the spark activity is well captured by the AE RMS parameter. As in the previous case, the MRR and the surface roughness (Ra and Rq) values exhibit an increasing trend as the AE RMS values increase.

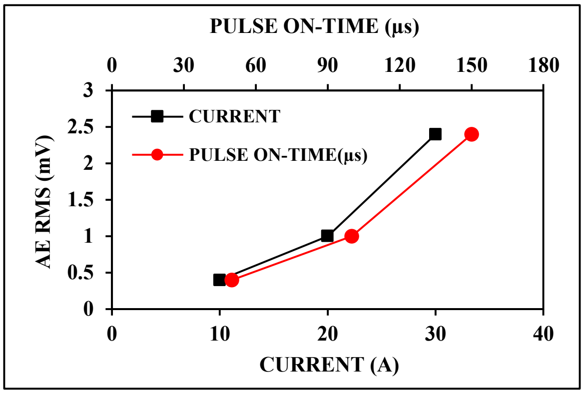

Fig. 7. (a) Comparison of AE RMS with current and T_{on}

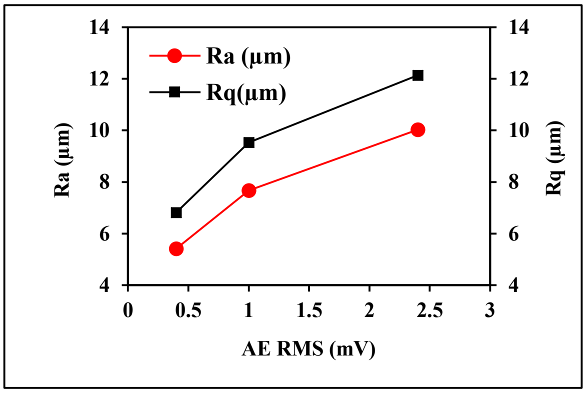

Fig. 7. (b) AE RMS vs. (Ra and Rq)

In an industrial practice, it is a very time-consuming process for the operator to monitor the MRR. The weight of the workpiece needs to be measured by the operator before machining. Then the machine will be started and the machining operation will be performed at a specific flushing level for some time. Then the machine has to be stopped, the workpiece has to be weighed again and the MRR used to be calculated. With the help of AE sensor, the operator needs to fit the AE sensor to the machine tank and can monitor the MRR using the acoustic emission signals as AE RMS proves to be a useful indicator of MRR. Similarly, the measurement of the surface roughness of the workpiece in EDM is generally a post-machining process where a suitable surface roughness measuring instrument is used to measure the roughness after machining. With the help of an AE sensor, in-process monitoring of the surface roughness of the workpiece in EDM could be realized ensuring quality control at the time of machining itself.

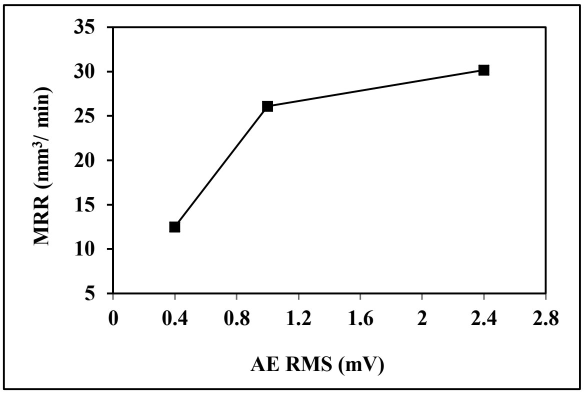

Fig. 7. (c) AE RMS vs. MRR

3.4 Data-driven model for prediction of Surface Roughness (Ra) and Material Removal Rate (MRR) using AE features

From the above discussions, it is observed that for the given experimental conditions, the selected acoustic emission features exhibit a similar trend with the discharge energy as the MRR and surface roughness. Sixteen experiments were conducted using a copper tungsten tool for various machining conditions. Workpiece used was similar to AISI D2 steel. The surface roughness (Ra) and the MRR values were measured as described in section 2. The AE signals were collected for all the 16 experimental conditions and the AE features namely AE RMS, signal strength and absolute energy were extracted. Two multiple linear regression models were built to predict the surface roughness (Ra value) and the MRR. A 95% confidence level was chosen while building the models. The two AE parameters namely AE RMS and signal strength were chosen as they were found to be having an intuitive physical meaning with respect to the AE phenomenon. These two AE parameters were also found to be significant based on the ANOVA table. The measured values of the output parameters namely Ra and MRR are listed in Table 8. The model parameters (AE features used in model building) are provided in Table 9.

Table 8. Process parameters with output variables

Experiment No.	Current (A)	Voltage (V)	T_{on} (µs)	Ra (µm)	MRR (mm^3/min)
1	10	40	50	7.00	9.336
2	10	80	100	8.03	15.840
3	10	120	150	12.24	24.364
4	10	160	200	10.84	16.287
5	20	40	100	9.24	20.905
6	20	80	50	8.20	26.614
7	20	120	200	11.57	25.071
8	20	160	150	11.12	20.057
9	30	40	150	12.70	35.888
10	30	80	200	12.58	28.581
11	30	120	50	7.90	27.976
12	30	160	100	10.80	19.067
13	40	40	200	13.28	23.682
14	40	80	150	13.07	30.149
15	40	120	100	10.28	41.707
16	40	160	50	8.51	29.648

Table 9. Model parameters

Experiment No.	AE RMS (mV)	AE Signal strength (3.05×10^6 pVs)
1	4.6	2.9575
2	1.5	0.4871
3	2.2	0.4782
4	2.9	0.8234
5	2.2	0.5899
6	4.3	1.7299
7	1.2	0.4997
8	1.0	0.1740
9	3.9	1.2682
10	1.9	0.3554
11	1.3	0.8087
12	1.9	0.4442
13	5.3	2.6344
14	1.7	0.4220
15	0.8	0.2810
16	3.5	2.1064

Two multiple linear regression models were built to predict the Surface roughness (Ra) and the MRR values.

- Model 1: EDM process parameters namely current and pulse on-time alone were used as predictor variables. As the gap voltage doesn't affect the discharge energy much, it was not considered in the predictor variable set.
- Model 2: AE features namely AE RMS, signal strength were added to the predictor variable set used in model 1.

The regression coefficients (intercept and the slopes) of both model 1 model 2 for both Ra and MRR prediction are presented in Table 10.The two models are compared for their prediction accuracy and the results are shown in Fig. 8 (a), (b).

Table 10. Regression coefficients of Model 1 and 2

	Coefficients			
	Model 1: For Ra prediction	Model 1: For MRR prediction	Model 2: For Ra prediction	Model 2: For MRR prediction
Intercept	5.103750	0	4.895817	0
Current	0.062350	0.628212	0.068401	0.710102
T_{on}	0.030380	0.067709	0.025511	0.020386
AE RMS			0.858226	4.294877
Signal strength			0.000015	-0.00007

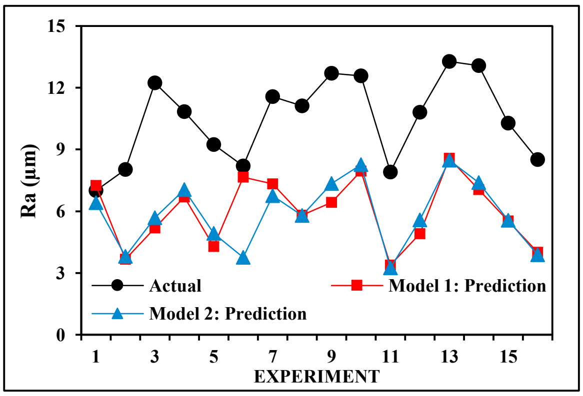

Fig. 8. (a) Predictability of Ra: Actual vs. Model 1 vs. Model 2

The MRR is zero when all the input parameters are zero. Hence while developing the prediction model for MRR, it is logical to assume the intercept to be zero. Regression through the origin can be adopted here. But in the case of Ra prediction, since the workpiece will have a certain initial surface roughness (surface roughness before machining) always, the same assumption becomes invalid.

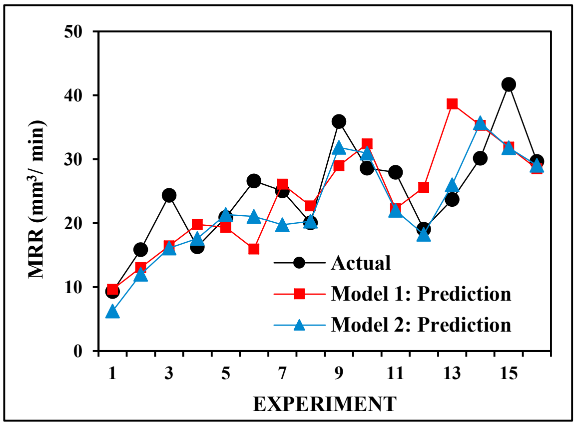

Fig. 8. (b) Predictability of MRR: Actual vs. Model 1 vs. Model 2

From Fig.8 (a) and (b) it can be observed that the prediction accuracy of the model 1 improves by the addition of the AE features to the predictor variable set. This is observed for both Ra and MRR prediction. This observation is also confirmed by comparing the Root Mean Square Error (RMSE) of prediction values for the two models as provided in Table 11. From Table 11, it is observed that the predictability of the model improves by the addition of AE features. Though the adjusted R^2 value for MRR prediction decreases, the RMSE is found to reduce.

Table 11. Regression statistics for model 1 and 2

	For Ra prediction		For MRR prediction	
Model	Adjusted R^2	RMSE of prediction (μm)	Adjusted R^2	RMSE of prediction (μm)
1	0.8148	4.8558	0.8962	6.5853
2	0.8528	4.7474	0.8495	5.9962

The set of experiments (1-16) in Table 8 was repeated twice to get some estimate of the repeatability and uncertainty of the results. All the experimental conditions were kept same as given in section 3.4.The model 2 which was developed incorporating the AE features for Ra and MRR prediction using the first set of experiments was validated for the two repetition sets. The results are presented in Table 12.

From Table 12, it is observed that the model shows a good repeatability of the surface roughness (Ra) and MRR prediction. This indicates that AE sensors have a good potential to be employed for monitoring the EDM process. Considering the potential system to system variations, more experiments can be conducted in future at different EDM environments using different process conditions. This will make the model more accurate, adaptable and robust.

Table 12. RMSE values for repetition sets

	For Ra prediction	For MRR prediction
Repetition	RMSE of prediction (μm)	RMSE of prediction (μm)
1	3.2223	6.6692
2	6.0021	7.4527

Conclusion

This work explores the possibility of employing AE sensors for process monitoring of EDM. The effect of EDM process parameters and the tool electrode material on the AE phenomenon in EDM was investigated in this study. Emphasis was placed on monitoring the surface roughness (Ra and Rq) and MRR using the AE signals. In light of above results, the following conclusions can be made.

- The AE sensor was mounted on the dielectric tank to monitor the EDM process. Though the AE waves attenuated in the dielectric medium before reaching the sensor leading to small amplitude and RMS values, the sensor location offered an advantage by making the process monitoring completely non-intrusive.
- Copper tungsten tool provided the strongest acoustic emission signal amongst all the tool materials used followed by graphite and copper for the given experimental conditions.
- AE was sensitive to the changes in the EDM process parameters such as current, voltage and T_{on}. AE RMS exhibited similar trend as the MRR and surface roughness (Ra and Rq) when these machining parameters were varied. Thus the spark activity in EDM is found to have a good correlation with the AE signals.

- The data-driven model built by incorporating the AE signal features along with machining parameters exhibited fairly good predictability for surface roughness (Ra) and MRR. Thus, for a well-characterized EDM system, AE can be a very useful indicator of both MRR and surface roughness.
- This paper presents some preliminary work done to explore the possibility of employing the AE sensing technology for effective process monitoring of EDM and signifies the capabilities of AE sensors in EDM. Keeping this research as a groundwork, the applications of AE sensor in EDM can be further extended to study important aspects such as tool wear, detect process anomalies such as arcing and short-circuiting, etc. The influence of workpiece material, machine gain, duty cycle, servo speed, etc. on the AE phenomenon in EDM can also be investigated in future which would broaden the potential of AE technology in EDM.

Acknowledgements

Authors thank the Department of Mechanical Engineering, IIT Madras for providing the necessary facilities to conduct the experiments. Authors acknowledge Mr. Lakshmi Narayanan (Technical Supervisor) and Mr.C.Gopalakrishnan (Technical assistant) for assistance provided in performing the experiments.

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