# Sustainable Eco-friendly Wire-cut Electrical Discharge Machining: Gas Emission Analysis

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**Research Article**

**Keywords:** Gas emission concentration, Material removal rate, relative Emission rate, WEDM, sustainable, near-dry

**Posted Date:** June 2nd, 2021

**DOI:** https://doi.org/10.21203/rs.3.rs-502937/v1

# Sustainable eco-friendly wire-cut electrical discharge machining: Gas emission analysis

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**Abstract**

Wire-cut electrical discharge machining (WEDM) is the highly essential unconventional electro-thermal machining process to cut the contour profile of hard materials in modern production industries. The various environmental impacting wastes (by evaporating and reacting hydro-carbon dielectric fluid) are produced during the WEDM process and these are harmful to the machine operators. These wastes are minimized by a near-dry WEDM process wherein the pressurized air mixed with a small amount of water is used as a dielectric substance. In this research, influences, and contributions of machining parameters such as air pressure, mixing water flow rate, spark current and pulse width on gas emission concentration (GEC), materials removal rate (MRR), and relative emission rate (RER) of sustainable near-dry WEDM process have been optimized by Taguchi analysis. RER is investigated to analyze the effects of machining factors on gas emission and machining rate combinedly. It was revealed that the maximum air pressure and flow rate of mixing water have significantly been promoting the sustainable near-dry WEDM process.

Keywords: Gas emission concentration; Material removal rate; relative Emission rate; WEDM; sustainable; near-dry.

## 1. Introduction

In the recent aerospace and automotive industries, wire-cut electrical discharge machining (WEDM) is an imperative recent cutting process to cut contour, accurate, intricate, and irregular profiles of thermal and electrical conducting sub-components. Furthermore, the best accuracy and highest surface finish of WEDM components are appreciated (Das and Chakraborty 2020). The gas emission from hydrocarbon fluid in the conventional EMD/WEDM process is unavoidable for the expectation of the highest production rate. As per ISO14000 environmental act, the gas emission and hazardous wastes emitted from such modern machining processes should be minimized to save the ecological system. The causes and effects of EDM wastes were analyzed by many EDM research experiments. The hydrocarbon and liquid dielectric fluids caused many harmful contaminants are exposed in the operating environments (Tonshoff et al. (1996). Leao and Pashby (2004)). Hence, the ecological impacts of EDM/ WEDM could be minimized by changing cutting fluids and modifying machining factors. However, the machining performance has been reduced while altering cutting fluid and operating procedures. It affects the production rate and leads to economic losses. Hence, sustainable eco-friendly EDM/WEDM research activities should be focused on improving machining performance and minimize pollutions. The sustainable development researches activities in EDM/ WEDM processes have been explained as follows.

The toxicity and flammability of waste streams generated during EDM processes are analyzed and compared. It was concluded that harmful waste produced could be varied by tool, work material, and dielectric fluid (Yeo et al. 1998). After the days, many research activities were promoted to control the waste stream of EDM. It was found that minimum hazardous material was detected from resin dialectic and softer work materials in WEDM and emitting low-level emissions. The energy consumption and waste impacts to the health of human operators, lands, water, and air pollutions have been concentrated and hydro-carbon fluid was replaced by tab water in EDM and WEDM processes(Boopathi and Sivakumar 2014; Tang and Du 2014). However, the machining efficiency has been decreased while replacing such dielectric fluid. In this aspect, ultrasonic, magnetic, and cryogenic assisted gas dielectric EDM processes improve the machining performances(Zhang et al. 2005, 2006; Singh Grewal and Parkash Dhiman 2019; Talebizadehsardari et al. 2020). Various groupings of work materials, tools, and dielectric fluid are affecting the various elements in the gas emissions (Evertz et al. 2006). It was revealed that the plasma zone temperature of EDM will generate the various toxic contaminants while using different work materials(Tonshoff et al. 1996; Valaki et al. 2015).

The dielectric level, current, pulse time, and flushing pressure were taken as factors to control the concentration of aerosol and optimum parameters setting had been predicted to optimize the lowest aerosol exposure(Mathew et al. 2010). It was also found that the maximum current and pulse time settings will increase toxic aerosol emission in the operating zone (Jose et al. 2010). The water dielectric in EDM processes has been reducing the toxic gas emission as compared to the existing process. Three sustainability indicators EDM have been identified as ecological impact, operator's health, and working safety. It was analyzed and concluded that dry EDM is an environment and operator-friendly sustainable process (Valaki et al. 2015). The sustainable EDM process has been investigated using canola and sunflower Biodiesel to promote clean and emit much less harmful emissions (Ng et al. 2017). Generally, the gas-assisted EDM was performed with low performance with a good environmentally supported process. The reducing negative impact of this process could be improved by replacing a minimal amount of eco-friendly fluids such as water mixed with gas mixed with air as dielectric fluid(Leppert 2018). The carbon emissions and machining noises of the magnetic flux assisted technique EDM process have been experimentally investigated to identify the machining setting for improving both environment and machining performances(Zhang et al. 2018). The economic and environmental factors (energy, electrode, and treatment of dielectric fluid) are experimented to analyze the harmful discharges and discarding of the dielectric medium by three pillars sustainability approach(Zia et al. 2019). The typical tap water dilutes in deionized water as a protecting medium in EDM experiments was attempted to reduce the machining pollution. It was concluded that the toxic contaminants have been reduced by diluted dielectric medium using Taguchi-grey analysis(Muthuramalingam 2019). The suitable EDM process had also experimentally been attained by water-in-oil (nano-emulsion) as insulation fluid. It has revealed that machining performance was also improved by that method(Dong et al. 2019). A study exhibited that the near-dry green EDM process decreased the 97% fume emission with maximum debris when compared to existing liquid EDM (Dhakar et al. 2019). It was reviewed that the water, gas, bio- dielectric have been utilized to promote sustainable development of dry and near-dry EDM processes(Singh et al. 2020). The vegetable oil-based dielectrics in wet, near-dry EDM processes was experimentally justified that the eco-friendly EDM performance had significantly been improved(Das et al. 2020). The electrode wear, energy, vapour density, current, and dielectric contaminants had been investigated superiority and inferiority ranking (SIR) method. It has been observed that to predict the best process parameter to improve the overall performance(Das and Chakraborty 2020).

In the above-mentioned literature, the gas emission analysis of near-dry WEDM investigations was not experimentally investigated. In this paper, the gas emission concentration, material removal rate, and relative emission rate of near-dry WEDM (small quantity of water and compressed air as dielectric) by Taguchi technique to predict the best machining setting for minimizing gas emission and relative emission rate with MRR.

<Insert Figure 1 about here>

# 2. Experimental method

## 2.1. Experimental setup

The fuzzy logic CNC-controlled WEDM machining is used to cut AISI D2 tool materials by 0.18mm molybdenum wire electrode. The sustainable near-dry WEDM conditions are listed in Table 1. The pictorial representation of the near-dry WEDM experimental arrangement is displayed in Figure 1. 7 mm thickness of the wire tool has been used to conduct the experiments. The wire tool is reciprocating with help of a servo motor and rollers. The compressed air and small quantity of water mixed is called air-mist instead of hydrocarbon as a dielectric fluid. The compressed air pressure and mixing water flow rate are measured by this special experimental setup. The machining parameters pulse duration and spark current have been controlled and observed by the WEDM control unit monitor. The pulse interval and gap voltage and wire tension are constantly maintained as 48 micro-second, 75V, and 10 N respectively. In the experimental setup, the complete WEDM machining zone is covered by a vacuum chamber in which the small holes are provided to enter the atmospheric air (Figure 1). The outlet pipe is connected to a dust collector which is made of paper material. The dust collector/ filter is connected to a vacuum pump to suck the gas from the machining zone. Thus, the dust particles emitted during the cutting process are collected in a filter (dust collector).

<Insert Table 1 about here>

## 2.2. Machining responses measurement

(i) The gas emission concentration (GES) is calculated by the ratio of the weight of filter after cutting process in specific time to initial weight of filter by Equation (1) (Thiyagarajan et al. 2014).

$$GES = {}^{(wt_a - wt_b}/_{T} \text{ mg/min} \qquad (1)$$

Where $wt_a$ - the initial weight of filter/dust collector paper before cutting process in milligram, $wt_b$ -the weight of filter paper before the cutting process in milligram, T – time of machining duration in minutes.

(ii) The material removal rate (MRR) is calculated by Equation (2) as follows.

$$MRR = {}^{(wt_m - wt_n}/_{T} \text{ mg/min} \qquad (2)$$

Where $wt_m$ - the initial weight of work materials\ before cutting process in milligram, $Wt_n$ - Weight of work material before the cutting process in milligram, T – time of machining duration in minutes.

(iii) The relative emission rate (RER) of the machining processes is calculated from the ratio of GES and MRR as following Equation (3) (Thiyagarajan et al. 2014). It is used to observe the quantity of gas emission to quantity of material removal during the specific time of the cutting process.

$$RER = \frac{GES}{MRR} \qquad (3)$$

<Insert Table 2 about here>
<Insert Table 3 about here>

### 2.3. Experimental design

The Taguchi L27 orthogonal array is applied to conduct the near-dry WEDM experiments by varying the machining parameters and making response observations. It is an effective design of the experimental (DOE) method to identify the influences of each factor with minimum numbers of the test. Initially, the trial tests were conducted to finalize the machining parameters levels. The value of each parameter level is shown in Table 2. The values of each parameter level have been finalized based on permitted ranges of parameters and the combination of parameters setting is implemented to measure the required results. The levels combination of air pressure, the flow rate of mixing water, spark current and pulse width are used to conduct the 27 trials of experiments as listed in Table 3. In this paper, the mean effect of parameters is considered to study the response variations. The influences and contributions of each parameter on gas emission concentration, material removal rate, and relative emission ratio are predicted by Taguchi analysis. The analysis of variance (ANOVA) is performed for the mean values of each factor. The Taguchi analysis of

GES, MRR, and RER are shown in Tables 4,5, and 6 respectively. The following formulae (Equations (4) – (8) ) are employed to find the internal terms of Taguchi analysis.

Total sum of Square $$SS_T = \sum_{i=1}^{k}(m_i^2 - (k \times m_t^2)) \tag{4}$$

Parameter sum of Square $$SS_P = \sum_{i=1}^{r}\left(\frac{sm_i^2}{r} - \frac{1}{k}\left(\sum_{i-1}^{k} m_i\right)\right) \tag{5}$$

Variance $$V_p = \frac{SS_P}{df_p} \tag{6}$$

Corrected sequential sum of square $$SS_C = SS_P - \left(df_p\right)(V) \tag{7}$$

Percentage of contribution $$C_{\%} = \frac{SS_P}{SSc} \tag{8}$$

Where 'k' represents the number of parameters, 'j' as the parameter level, $m_i$ as the mean value of ith experiment, $m_t$ as the total mean value, $sm_j$ as the sum of the value of $j^{th}$ as level of the parameter, 'r' as the number of repetition, and $df_p$ as the degree of freedom.

## 3. Results Analysis and Discussions

### 3.1 Analysis of GEC

It was observed from Taguchi analysis that the spark current and air pressure significantly affect the mean value of GEC. The percentage (%) contribution of machining factors, i.e., spark current (45.78%), air pressure (32.03%), and pulse width (18.15%) have been higher than the flow rate of mixing water (2.79%) on GEC.

<Insert Table 4 about here>

It was observed from Table 4 that the percentage contribution of spark current on GEC was 45.78%. It revealed that current is providing an important impact on the GEC of the reacting dielectric fluid as shown in Figure 2. While increasing current, the gas emission is also increased due to an increase in the concentration of spark energy in the cutting zone(Thiyagarajan et al. 2012; Dhakar et al. 2019). It is caused by the increasing thermal reaction between work material and a wire tool. Thus, the gas emission will be increased in the machining atmosphere/ zone. The air pressure has the second-highest contribution on the GEC by increasing the dielectric strength and reducing evaporation of dielectric fluid due to minimum reaction of water with burned metal. While increasing the air pressure, the machining performance will be improved and material debris also increased(Boopathi and Sivakumar 2014). However, a small amount of mixing water is only evaporated and metal is completely burned during the cutting process. It caused the gas emission mixing with the surrounding air is decreasing while increasing air pressure (Suthangathan Paramashivan et al. 2012).

<Insert Figure 2 about here>

The emission concentrations increased by the increase in pulse width due to high heat energy, evaporation, and metal melting are directly varied to the quantity of pulse heat by pulse time(Evertz et al. 2006; Sivapirakasam et al. 2011; Suthangathan Paramashivan et al. 2012; Thiyagarajan et al. 2012). The high heat debris particles will react with water which causes the smoke by long availability of spark in the cutting zone(Spedding and Wang 1997; Pandey et al. 2015; Sadagopan and Mouliprasanth 2017). The flow rate of water mixing with air was less contribution on GEC (2.79%) due to mixing water had atomized by high-pressure air in the cutting zone. While increasing flow rate from 8 to 12 ml/min, the maximum portion of water has been perfectly mixed with pressurized air and from 12 to16 ml/min, un-atomized water particle reaction with debris, then the GEC is getting increased. In the near-dry WEDM process, the gas emission by the burning of dielectric fluid will be deceased at the flow rate of 12 ml/min. thus, the near-dry WEDM process is representing as a Green machining process(Pandey et al. 2015; Valaki et al. 2015; Dhakar et al. 2019; Singh et al. 2020).

<Insert Table 5 about here>

### 3.2 Analysis of MRR

It was revealed from Table 5 that the percentage of contributions of spark current, pulse width, air pressure, and flow rate of mixing water on MRR is 33.71%), 23.42%, 31.78%, and 8.68% respectively.

<Insert Figure 3 about here>

It was indicated from Taguchi analysis (Figure 3) that the moderate air pressure (5 bar) improves the MRR due to efficient flushing and sufficient cooling effect in the near-dry WEDM process(Boopathi and Sivakumar 2012; Boopathi and Myilsamy 2021). At the low air pressure (3 bar), the metal debris is reduced due to insufficient spark in the plasma zone. The spark transfer between wire and workpiece materials has been disturbed by increasing pressure to 7 bar (Boopathi and Sivakumar 2013, 2014, 2016). While increasing the mixing water flow rate, the MRR is increased due to effective cooling and an increase in dielectric strength in the cutting zone(Boopathi and Sivakumar 2012). The spark current and pulse width are significantly contributing to improving the MRR due to high thermal energy, high melting, and vaporization of metal in the cutting zone(Abbas et al. 2012; Kumar et al. 2020).

<Insert Table 6 about here>

### 3.3 Analysis of RER

The effects of machining parameters on the RER of near-dry WEDM are shown in Figure 4. It was also revealed from Table 6 that the percentage of contributions of air pressure, the flow rate of mixing water, spark current, and pulse width on RER are 85.01%, 9.36%, 3.52%, and 0.81% respectively.

It was observed from Table 6 that air pressure has the highest contribution than mixing water flow rate, pulse width and spark current on RER. the pressure is directly proportional to expectations of both responses (MRR and gas emission) due to high air pressure promotes green machining processes(Dhakar et al. 2019; Ming et al. 2021). It was also revealed from the literature the dielectric medium is a significant factor in gas emission in EDM processes(Leão and Pashby 2004; Chakraborty et al. 2015; Ng et al. 2017; Singh et al. 2018). In the near-dry WEDM processes, the liquid/ hydrocarbon dielectric fluid has been replaced by air or air mixed with a small amount of water to control the emission.

<Insert Figure 4 about here>

While increasing the flow rate of mixing water, the RER also decreased due to effective cooling, good dielectric strength and flush-out debris effectively in the cutting zone. The highest quantity of water (16 ml/min) provides sufficient dielectric strength and cooling effect in the cutting zone. The spark current and pulse width parameters are giving inverse influences on gas emission and MRR. Thus, these factors were insignificant and less contribution to RER. However, the lowest values of spark current and pulse time will promote the eco-friendly machining process (Figure 4).

<Insert Table 7 about here>

### 3.4 Prediction and confirmation experiments

The optimum machining parameter settings for minimizing the gas emission and RER, and maximize the MRR are shown in Table 7. The optimum machining parameter settings to minimize GEC (0.179 mg/min) were air pressure (7 bar), flow rate (12 ml/min), spark current (3 A), and pulse width (16 µs), and predicted value was at best parameter setting. The predicted GEC value was validated by a confirmation experiment (0.181 mg/min). The optimal machining parameter settings to maximize the MRR (105 mg/min) were air pressure (5 bar), flow rate (16 ml/min), spark current (5 A), and pulse width (28 µs). The predicted MRR value was validated by a confirmation experiment (106 mg/min). The best machining parameter setting to minimize the RER (0.0057) were air pressure (7 bar), flow rate (16 ml/min), spark current (3 A), and pulse width (16 µs). The predicted RER value was validated by a confirmation experiment (0.006).

## 4 Conclusions

In this research, the GEC, MRR, and RER of sustainable near-dry wire-cut EDM process have been analyzed using the Taguchi method. The following conclusions were derived as follows.

- The gas emission concentration (GEC) has been reduced by minimizing pulse width, spark current, and flow rate of mixing water and maximizing air pressure. Air pressure increases the dielectric strength and reducing the evaporation of dielectric fluid due to the minimum reaction of water with burned materials. The moderate flow rate of water gives the lowest emission due to avoiding the chemical reaction of unburned materials. The current and pulse width enhance the gas emission rate because of the highest debris by maximum intensity of long spark energy in the cutting zone.
- The MRR has been improved by increasing pulse width, spark current, and flow rate of mixing water. It is maximum at moderate air pressure (5 bar) due to efficient flushing and sufficient cooling effect in the cutting zone. The pulse width and current improved the MRR because of the highest debris by the good intensity of a long spark. The highest flow rate of water improves the MRR due to sufficient dielectric strength with good flushing efficiency.
- The relative emission rate (RER) was reduced by the lowest input of spark current, pulse width, and highest value of air pressure and mixing water flow rate due to sufficient dielectric strength and chilling effect in the cutting zone. While increasing air pressure, RER is getting reduced due to the complete burning of materials at maximum pressure. RER is reduced by the minimum intensity of spark at the low value of pulse width and spark current levels.

- The air pressure was the highest contribution (85.01%) on relative emission rate by increasing pressure minimize the gas emission and improves the materials debris. Hence the air pressure is one of the key parameters to enhance the sustainable near-dry wire-cut EDM process.
- The predicted values of GEC, MRR, and RER from Taguchi analysis have been validated by a set of confirmation experiments.

**Acknowledgment Author**

The author thanks Mechanical Engineering at Bannariamman Institute of Technology, Sathayamanagalam, Erode, Tamilnadu, India. for helping to carry out this research work.

**Ethics approval**

Not Applicable

**Consent to participate**

Not Applicable

**Consent for publication**

Not Applicable

**Authors Contributions**

Dr. Boopathi Sampath contributed to conducting experiments, experimental design, analyzing and interpreting the data regarding the near-dry WEDM Process.

**Funding**

No fund received.

**Competing Interests**

The author declares that he has no competing interests.

**Availability of data and materials**

The datasets generated during and/or analyzed during the current study are available from the corresponding author and included in this article.

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# Figures

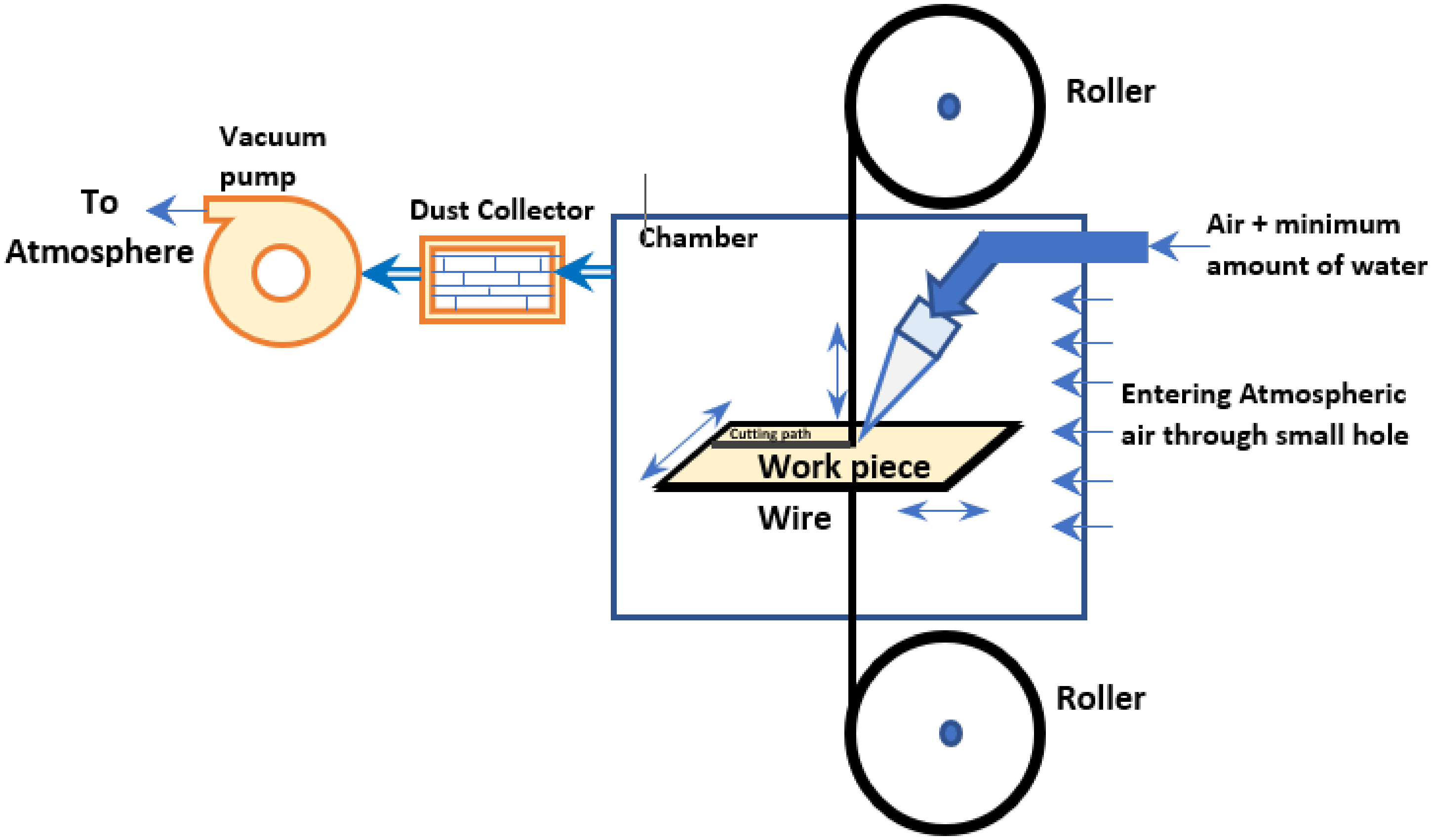



**Figure 1**

Graphic drawing of near-dry wire-cut EDM experimental arrangement to measure the gas emission concentration

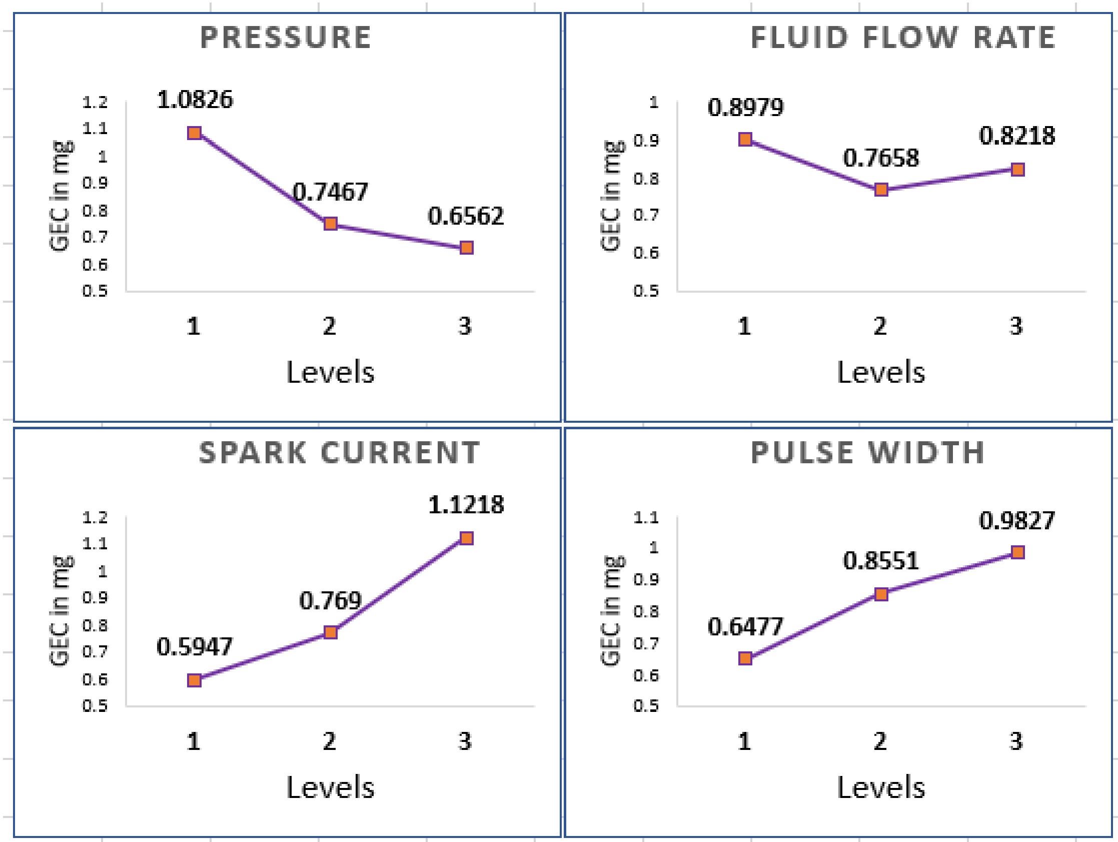
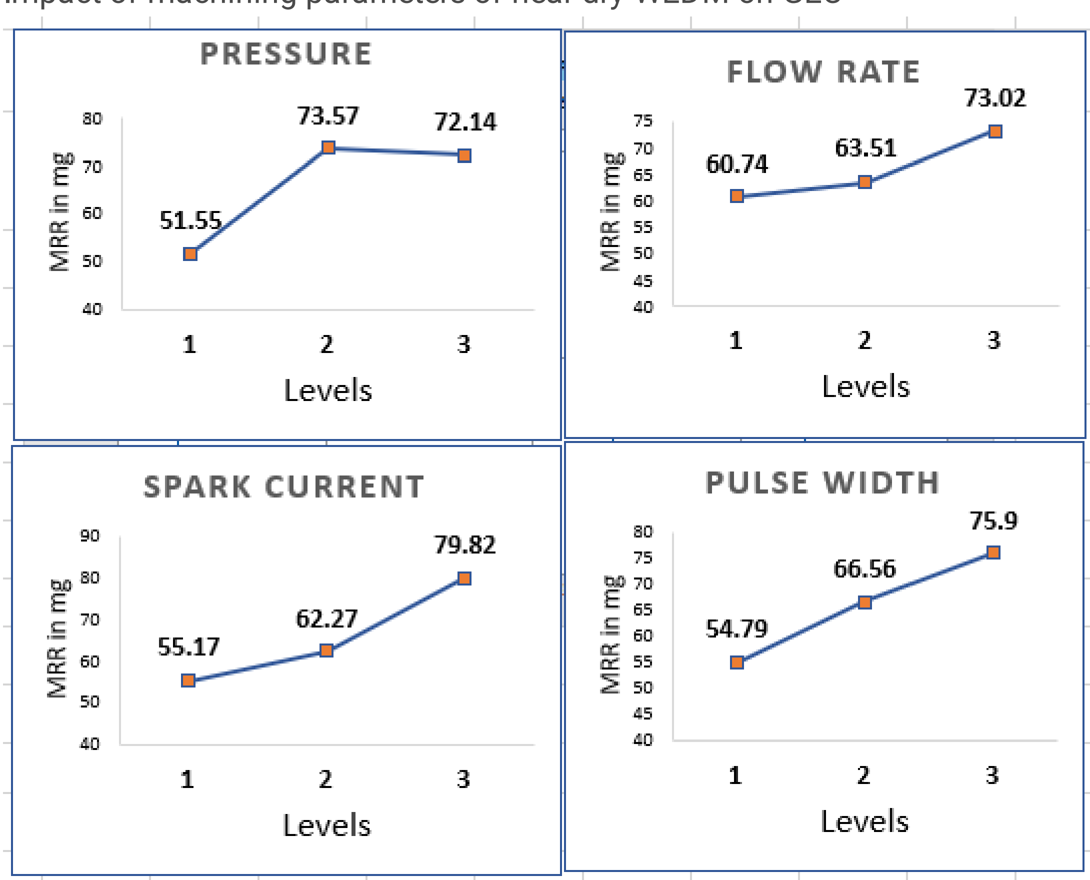


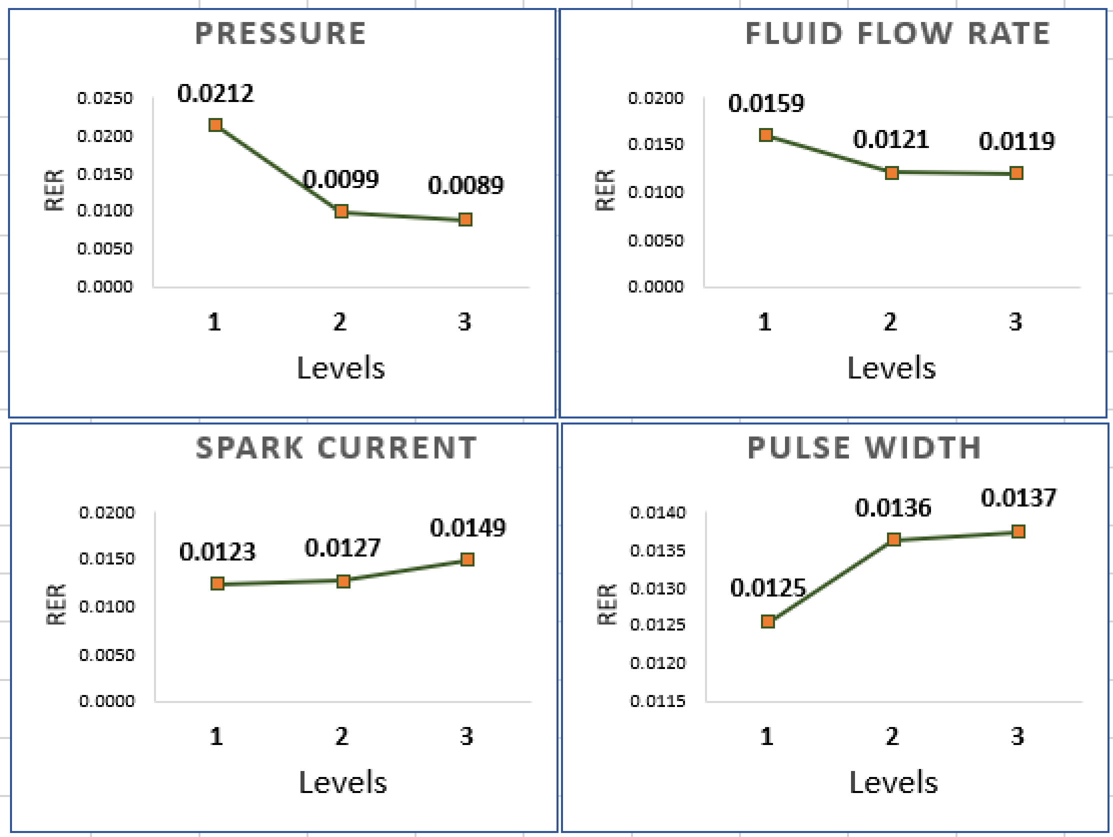

**Figure 2**

Impact of machining parameters of near-dry WEDM on GEC



## Figure 3

Impact of machining parameters of near-dry WEDM on MRR




## Figure 4

Impact of machining parameters of near-dry WEDM on RER