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Short Communication

Improvement of Micro-Electrochemical Discharge Machining of Austenitic Stainless Steel 316L using NaOH electrolyte containing N_2

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Micro-Electrochemical discharge machining (µECDM) is a subjective choice in delicate micro machining operations, particularly in Micro-Electromechanical Systems (MEMS) industries for fabricating the microscale devices. Dielectric characteristic of electrolyte is a predominant parameter determining the performance of µECDM. Prevention of surface cracks, heat-affected zone, and surface irregularities on the machined specimen are research challenges that striving to find innovative experimental designs. This research adopts a new experimental setup where Nitrogen gas is introduced in the gap between the tool electrode and workpiece. The experiments were conducted using plain aqueous NaOH and Nitrogen gas assisted aqueous NaOH electrolytes in µECDM of Austenitic stainless steel 316L (SS 316L). Voltage, duty cycle, electrolyte concentration, and Nitrogen gas flow rate were varied to investigate the responses of the machining process namely Material removal rate (MRR) and Tool wear rate (TWR). The dielectric characteristic of the generated gas film has improved the current density across the gap and consequently enhanced the heat transformation from the spark through the discharge and hydrodynamic regimes to the workpiece effectively. Nitrogen gas assisted µECDM has produced MRR of 2.6 mg/min and TWR of 0.8 mg/min at 105V, 70 duty cycle, 15.708 wt% of NaOH electrolyte and 3 lit/min of Nitrogen gas flow. SEM and EDX results have evidenced the minimum surface irregularities which indicates the uniform metal removal on the machined components. The results of the confirmatory experiment reveal that there is about 10% of increase in MRR and 21% of decrease in TWR are achieved from Nitrogen gas assisted machining, compared to plain NaOH electrolyte machining.

Keywords: µECDM, NaOH electrolyte, voltage, duty cycle, electrolyte concentration, MRR, TWR

1. INTRODUCTION

Electrochemical Discharge Machining (ECDM) is a kind of non-conventional hybrid machining process that combines the features of Electrical Discharge Machining (EDM) and Electro-Chemical

Machining (ECM) to machine the brittle and difficult-to-machine materials. Surface finish, hardness, and residual stresses are negatively changed, if the right machining process is not chosen [1]. In recent days, Micro-Electrochemical discharge machining (μECDM) is proven to be an efficient micro-machining process especially for micro-fabrication industries [2]. The major advantage of μECDM is that it is completely independent of the electrical conductivity of materials when compared to Electric discharge Machining (EDM) and Electrochemical Machining (ECM) processes [3]. Moreover, the challenges involved in fabricating the micro-scale components using other machining processes is reasonably overcome by the μECDM. Hence, it is employed in fabricating a lab-on-a-chip (LOC) device, micro-robot components, micro electromechanical systems (MEMS), automation components of automotive and components of marine industries [4]. In μECDM, the material removal is achieved by the generation of thermal sparks and chemical etching between the tool electrode and electrolyte. The aqueous NaOH, $NaNO_3$, KOH, Na_2SiO_3 electrolytes with different concentrations have been used to machine materials like Glass, Ceramics, Stainless Steel, Quartz, etc. [5].

Most of the researchers have chosen stainless steel as a tool electrode for investigating the performance of μECDM despite commonly available tungsten carbide, tungsten, copper, high carbon steel, and high-speed steel. It is because of the use of aqueous NaOH electrolyte, which is a corrosive agent, and it affects the surface of the tool electrode very easily. The surface texture of the electrode plays a significant role in the coalescence of generated bubbles. These bubbles are responsible for making the gas film between the tool electrode and workpiece. Substantial research can be found on μEDM, whereas only a few research has been done in μECDM as it is a up-trending machining method. Just to top up the above statement, some of the recent researches are listed below. Manivannan Raja [6] investigated μEDM of case hardened AISI 304 stainless steel, utilizing cryogenic cooling effect. They reported that upto 70% of increase in MRR can be received in cryogenic cooling of micro EDM. Hang Yusen investigated the method to reduce the recast layer of inclined micro hole in ECDD. They suggested that the step feeding of electrode and increase in pause time of electrode will reduce the recast layer thickness in inclined micro holes of aerospace engine turbine blades [7]. Chenxue Wang and Qiang [8] reported that Al powder added EDM oil could increase MRR during μEDM of Inconel 706 steel. Nagarajan [8] used slotted copper rod as a modified tool to achieve the better performance in μEDM of LM13 Al alloy. Md Al-Amin [10] used hydroxyapatite powder and carbon nanotubes suspended electrolyte for achieving the greater tool life in μEDM. Tingting Ni [11] investigated the effect of introducing deionized water as an electrolyte in μEDM, where the discharge energy was increased with the increase of capacitance and open-circuit voltage, which subsequently melted more materials and vaporized, leading it to the crater volume. Shaojie Hou and Jicheng Bai [12] collected 100 discharge craters through repeated experiments with different parameter combinations and used them to develop a stochastic prediction model of μEDM. Bindu Madhavi [13] produced micro holes of 500 μm on borosilicate glass through μECDM, for which they optimized the machining parameters using S/N ratio method. Rathore and Dvivedi [14] employed sonication during μECDM that regulated the departure radius of gas bubble and subsequently the thickness of gas film. This method of machining has increased MRR by 11.13%. Ladeesh and Manu [15] augmented grinding action using diamond core drill in addition to chemical action in μEDM. Bijan Mallick [16] attempted a mixed electrolyte with the combination of NaOH and KOH at the ratio of 1:0, 3:1, 1:1, 1:3 and 0:1 to investigate their effect on µECDM and reported that 1:3 ratio of the mixed electrolyte is better to result the lower tool wear and surface roughness. J. W. Schmidt analyzed the relative dielectric permittivity of Nitrogen gas at different temperatures and pressure [17]. The dielectric strength of gas film provides the quality of spark and subsequently to have the uniform current density across the gap. Nitrogen gas is one of the gaseous dielectric mediums and this will be responsible to improve the dielectric characteristics of the gas film[18]. So far, no research has been attempted to utilize the Nitrogen gas for improving the gas film characteristics. Hence the current research has focused on introducing Nitrogen gas assisted aqueous NaOH electrolyte in µECDM on Austenitic stainless steel 316L (SS316L) and conducting repeated experiments with different process parameters to investigate the effect of it in the machining. To this end, this article is organized as below; Section 2 details the modified experimental setup and method of research, Section 3 presents results and discusses the findings, while section 4 presents concluding remark.

2. MODIFIED EXPERIMENTAL SETUP AND METHOD OF RESEARCH

The schematic view of a modified µECDM setup is shown in Figure 1. A DC power source with the pulse generator is used to provide the voltage across the tool electrode (cathode) and auxiliary electrode (anode). The potential difference between these electrodes makes the electrolysis, resulting formation of bubbles near both electrodes. The critical voltage keeps on increasing these bubbles and creates a dense and coalescent into a gas film. [19,20]. In the modified experimental setup, regulated Nitrogen gas is sent and mixed with NaOH electrolyte. The generated hydrogen gas film between the tool and workpiece acts as a dielectric medium and it prevents to form the spark due to its insulation nature. If the applied voltage exceeds the critical voltage (voltage required to break the gas layer to make a spark), thermal erosion on the workpiece is started.

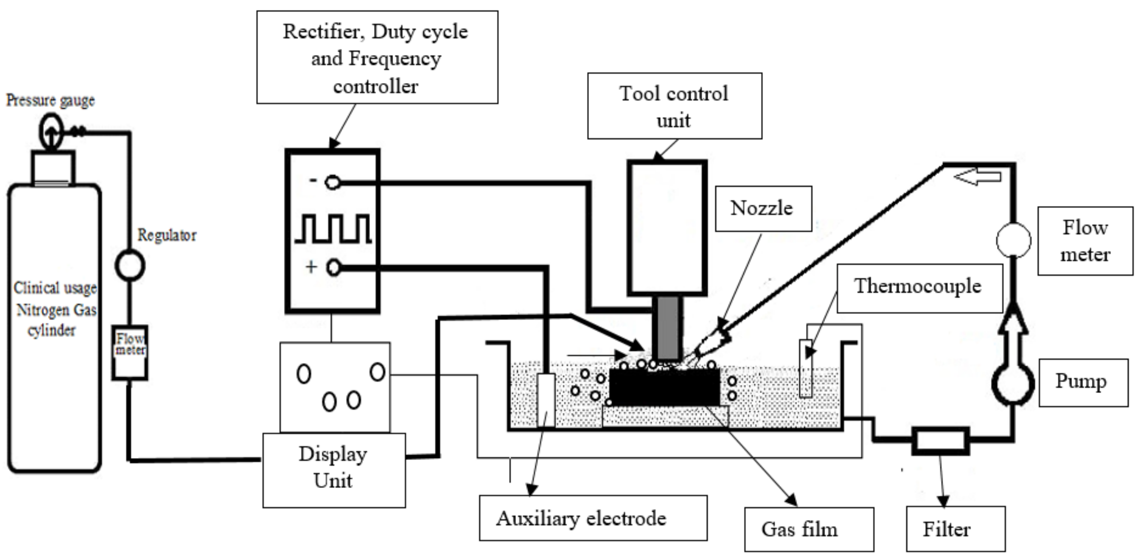


Figure 1. Schematic view of a modified µECDM setup

In µECDM, the gas film has two regimes namely discharge and hydrodynamic. The metal removal is effectively done at the discharge regime which is below 300 µm in depth. In the hydrodynamic regime (above 300 µm depth), the generated gas film may not be stable and hence, resulting in low metal removal [21]. The axial tool wear depends on voltage, the diameter of the electrode, electrolyte density, melting point of tool electrode material, and spark intensity [23,24]. The selected material for this experimentation is Austenitic stainless-steel grade 316L. It has a maximum carbon content of only 0.03%. The chemical composition of SS316L is presented in Table 1.

Table 1. Chemical composition of SS 316L

SS316L (wt%)	C	Mn	Si	Cr	Mo	Ni	N
	0.03	1.90	0.74	17.7	2.75	13.0	0.07

The optimal selection of major influencing parameters in µECDM is the way to obtain surface crack free machined specimen, minimum heat affected zone (HAZ), thermal fatigue, dielectric characteristics of gas film, and uniformity of current density [16]. Hence, Central Composite Design (CCD) of Response Surface Methodology (RSM) was used to do experimental design. To start with, the experimental design was done with machining parameters such as voltage, duty cycle, electrolyte concentration, and Nitrogen gas flow rate with constant current frequency of 5000 Hz. Since four independent variables were involved in this design, 31 experimental combinations were arrived (L_{31}). Clinical purpose Nitrogen gas cylinder with a pressure gauge and flow regulator valve was used to supply regulated nitrogen gas into the NaOH electrolyte. The capacity of Nitrogen gas cylinder is 10 litre (1.5 m^3) with pressure of 150 psi. To prevent the formation of monohydrates of NaOH, it was decided to prepare less than 40wt% concentration of NaOH as electrolyte for experimentation. While preparing the various concentration of NaOH electrolyte, the electrolyte temperature was measured using a Type K thermocouple to ensure that there was no sudden raise of the temperature. The workpiece and auxiliary electrode were immersed with an aqueous electrolyte and the tool electrode tip was immersed with the electrolyte solution. The position of the electrode was maintained with a minimum distance from the workpiece, resulting an initiation of the spark from the tool to the gas film. In each experiment, the sample of 10 mm×10 mm×3 mm was machined for a complete duration of 5 minutes without any interruption. The greatness of µECDM is that it is a non-short circuit process when compared to ECM. In every experiment, the material loss in both tool electrode and workpiece was measured before and after machining using the electronic weighing machine with 0.001g accuracy and Material removal rate (MRR) and Tool Wear Rate (TWR) were arrived from them.

During the spark discharge, the tool electrode bombarded a large number of electrons on the workpiece surface. Bombardment of these electrons raised the temperature of the work material resulting melting of the workpiece to achieve the metal removal [24]. Understandingly, the Nitrogen gas was preventing the heat lost to surroundings and consequently helped to transfer the adequate heat from the discharge regime to the hydrodynamic regime. This in turn assisted in getting better metal removal and lower tool wear. In addition to that, nitrogen gas acted as a dielectric gaseous medium and stable the formation of a gas film. The current mechanism of material removal was witnessed in the results observed. The discussion of results is presented in the following Section 3. Table 2 lists the combination of parameters used in the experiments.

In order to get the control data, experimental design was conducted for plain NaOH electrolyte condition where, only three control parameters such as voltage, duty cycle, electrolyte concentration was considered. Since it has only 3 parameters, L_{20} combinational datasets were arrived as tabulated in Table 3. Experiments were conducted with no nitrogen gas environment, and MRR. TWR and surface roughness for each sample was recorded.

Table 2. Experimental design and combination of parameters used in µECDM with Nitrogen gas assisted NaOH electrolyte

Run order	Voltage (V)	Duty cycle	NaOH concentration (wt %)	Nitrogen gas flow rate (lit/min)	MRR (g/min)	TWR (g/min)
1	135	50	15.708	3	0.0004	-0.0300
2	120	40	10.472	2	-0.0016	-0.0014
3	90	60	20.944	2	0.0002	-0.0012
4	90	60	10.472	4	-0.0006	-0.0010
5	120	60	10.472	2	0.0006	-0.0006
6	120	60	20.944	4	0.0014	-0.0006
7	105	50	15.708	3	-0.0018	-0.0006
8	90	60	10.472	2	0.0004	-0.0006
9	105	50	15.708	3	-0.0018	-0.0002
10	90	40	20.944	2	-0.0004	-0.0002
11	120	40	20.944	4	0.0004	0.0000
12	90	60	20.944	4	0.0014	0.0000
13	105	50	26.18	3	-0.0006	0.0002
14	120	40	10.472	4	-0.0018	0.0002
15	120	40	20.944	2	0.0008	0.0002
16	120	60	20.944	2	0.0008	0.0002
17	105	50	5.236	3	0.0002	0.0004
18	105	50	15.708	3	0.0012	0.0004
19	105	30	15.708	3	-0.001	0.0006
20	105	70	15.708	3	0.0026	0.0006
21	105	50	15.708	3	0.0004	0.0006
22	90	40	10.472	4	-0.0004	0.0008
23	90	40	10.472	2	0.0006	0.0008
24	105	50	15.708	3	-0.0002	0.0010
25	90	40	20.944	4	0.0008	0.0010
26	75	50	15.708	3	-0.0014	0.0012
27	105	50	15.708	3	0.0004	0.0012
28	105	50	15.708	1	0.0004	0.0012
29	120	60	10.472	4	-0.0006	0.0014
30	105	50	15.708	5	0.0014	0.0016
31	105	50	15.708	3	0.0002	0.0022

Table 3. Experimental design and combination of parameters used in µECDM with plain NaOH electrolyte

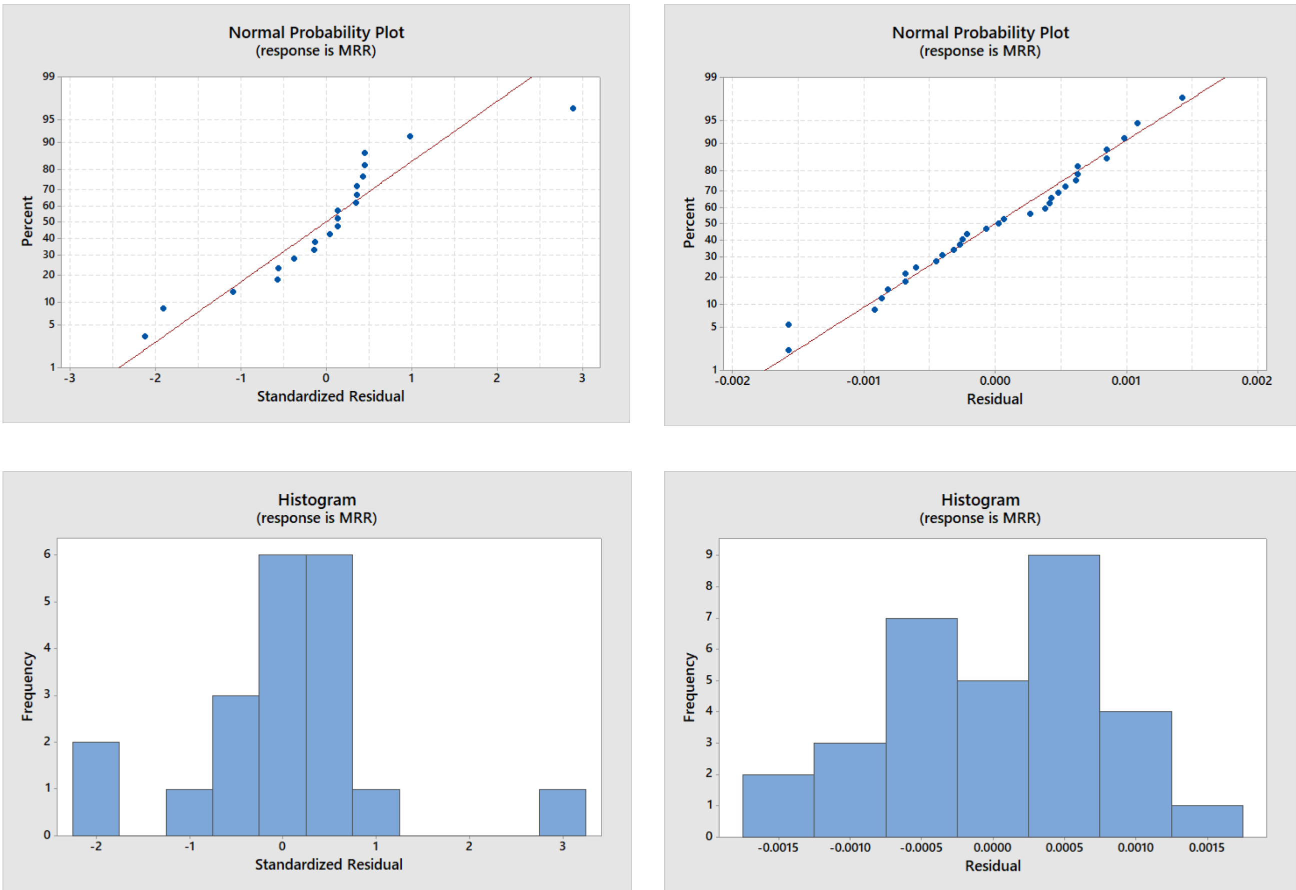
Run Order	Voltage (V)	Duty cycle	NaOH concentration (wt %)	MRR (g/min)	TWR (g/min)
1	90	60	10.472	0.001	0.0008
2	105	50	6.902	0.001	0.0004
3	105	33	15.709	0.001	0.0004
4	80	50	15.709	0.000	0.0020
5	120	40	10.472	0.002	0.0010
6	90	60	10.472	0.001	0.0012
7	120	40	20.945	0.000	0.0036
8	90	40	20.945	0.001	0.0008
9	105	50	24.515	0.000	0.0006
10	105	50	15.709	0.001	0.0006
11	120	60	20.945	0.001	0.0006
12	105	50	15.709	0.001	0.0024
13	105	67	15.709	0.001	0.0006
14	90	40	10.472	0.000	0.0004
15	130	50	15.709	0.004	0.0008
16	105	50	15.709	0.001	0.0012
17	105	50	15.709	0.001	0.0006
18	105	50	15.709	0.001	0.0006
19	120	60	10.472	0.000	0.0004
20	105	50	15.709	0.000	0.0002

3. RESULTS AND DISCUSSION

A total of 51 experiments were conducted, in which 20 experimental data refer to plain NaOH electrolyte-based machining and 31 experimental data refer to nitrogen gas assisted machining. The impact of Nitrogen gas assisted aqueous NaOH electrolyte on the µECDM of SS 316L is evidenced from the results. There are a few statements published from the past research regarding the metal removal mechanism. The metal removal is occurred if switching phenomenon generates electrical sparks rather than the breakdown of the insulating gas layer. In contradiction to that, Jalali [25] stated that metal removal is the combination of local heating and chemical etching. Jain [26] proposed arc discharge valve theory that is responsible for the removal of metal from the workpiece. It is understood from the current investigation that the metal removal might be happened due to localized melting of the workpiece caused by penetrated heat from the spark through both regimes of gas film to the workpiece. Chemical etching, and thermal erosion must have assisted the metal removal mechanism. The characteristic of the gas film, especially its stability on discharge and hydrodynamic regimes has significantly improved the performance of µECDM.

3.1 MRR analysis through Residual plots and Histograms:

One of the important methods of data analysis is residual plot, through which model validation can be done. The variations in the predicted and experimental values are observed and plotted in residual plots [27]. Figure 2 shows the residual plots of MRR and TWR during µECDM of SS316L specimens using plain aqueous NaOH electrolyte and Nitrogen gas assisted aqueous NaOH electrolyte. Strong evidence of minimal variation of data is observed from Nitrogen gas assisted µECDM machining. It confirms the uniformity of the experiments, where Nitrogen gas, as one of the dielectric gas media has influenced the dielectric characteristic of generated gas film between the tool electrode and workpiece. Subsequently, generated gaseous film and its dielectric characteristic has generated high quality sparks that resulted high MRR and TWR.



(a) MRR when using plain aqueous NaOH Electrolyte

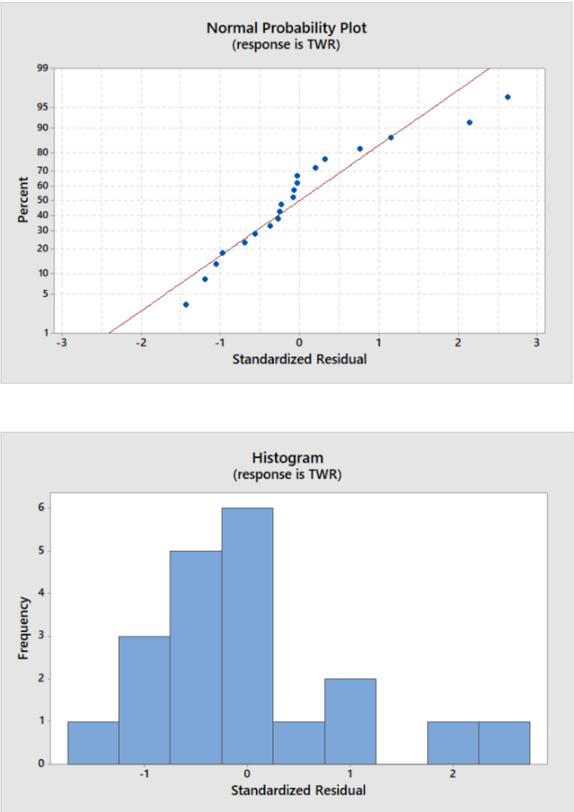
(b) MRR when using Nitrogen assisted aqueous NaOH Electrolyte

Figure 2. Residual and its distribution plots for MRR

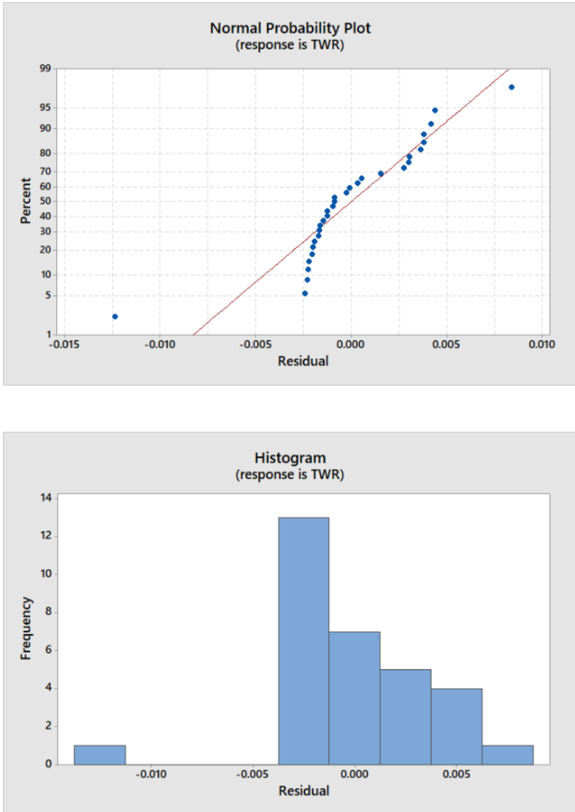
Knowingly in µECDM, current density varies along with the variation and instability of gas film and this variation of current densities across the gap affects the surface finish, MRR, and TWR. Hence, histogram was plotted and analyzed. The histogram that represents the most frequently occurred residual values and the nature of spreading over the residual values across the experimentation. The normal distribution of frequency is evidenced in Nitrogen gas-assisted µECDM when compared to experiments conducted using plain aqueous NaOH. This augments that the Nitrogen gas significantly improves the MRR.

3.2 TWR analysis through Residual plots and Histograms:

In μECDM, axial tool wear is occurred along with metal removal at the workpiece due to melting of tip of the tool electrode [28]. In the nitrogen gas assisted μECDM, deposition of auxiliary anode metal into the tool electrode was occurred. The electrolysis action is done at the electrolyte, and hence there is a chance of deposition of auxiliary electrode onto the tool electrode. It was observed when measuring the weight difference of tool electrode before and after machining. It is clearly evidenced in left skewed histogram as shown in Figure 3(b).



(a) TWR when using Plain aqueous NaOH Electrolyte



(b) TWR when using nitrogen assisted aqueous NaOH Electrolyte

Figure 3. Residual and distribution plots for TWR

3.3 Effects of influencing parameters on MRR and TWR:

Figure 4 shows the effect of selected influencing parameters on MRR and TWR while μECDM of SS 316L using plain aqueous NaOH and Nitrogen gas assisted aqueous NaOH electrolytes. The critical voltage, which is required to break the gas film in order to initiate the spark, plays a significant role in obtaining better MRR and TWR. It is observed that the voltage range 110-115 V with higher electrolyte concentration makes a better yield than that of the lower range of both voltage and electrolyte concentration.

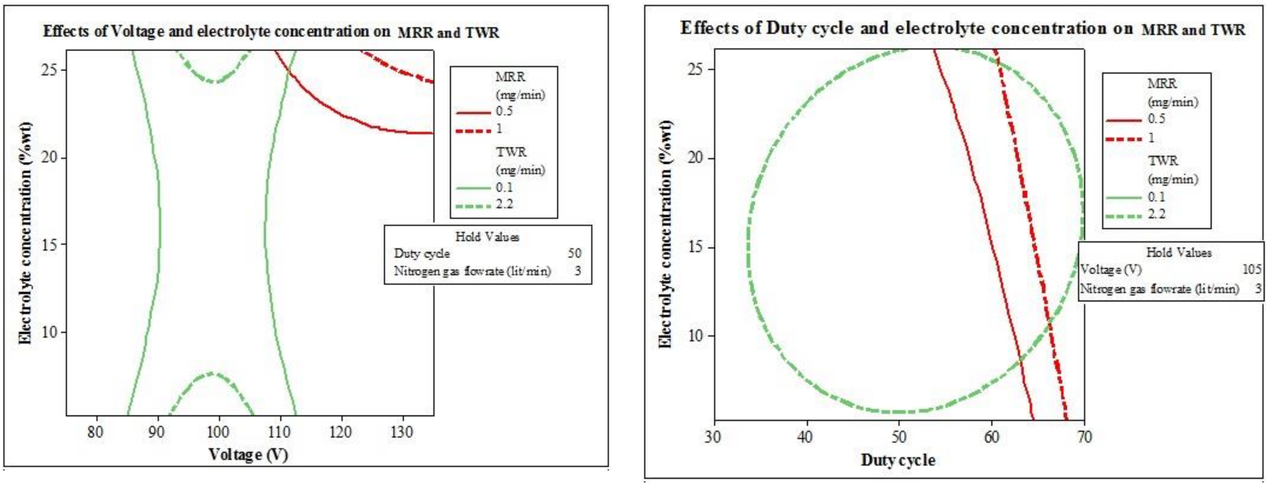


Figure 4. Effects of influencing parameters on MRR and TWR

Higher voltage is preferred for obtaining gas film with more stability due to the rise in temperature of the tool electrode [27,28,29]. The Nitrogen gas is directly influencing to enhance the MRR and lessen the TWR by the way of improving the dielectric characteristics of electrolytes. However, a higher range of duty cycle significantly improves the MRR and there is no solid evidence obtained through this experimentation for identifying its effect on TWR. Duty cycle with respect to electrolyte concentration shows the declined trend i.e., higher electrolyte concentration with a lower range of duty cycle performs better in obtaining MRR. The salient feature observed from this analysis is that the effect of duty cycle is observed only after 50. Minimum TWR is observed between the voltage of 85 and 115 irrespective of electrolyte concentration. The electrolyte concentration influences MRR more significantly rather than TWR. Electrolysis and chemical etching is seen controlled by electrolyte concentration.

3.4 Effect of Nitrogen gas flow rate on MRR and TWR:

The impact of Nitrogen gas flow rate on MRR and TWR is investigated, and the results are presented in Figure 5. The optimal selection of Nitrogen gas flow rate is mentioned as a circular region. The chosen values of gas flow rate within the circular region yielded the better performance.

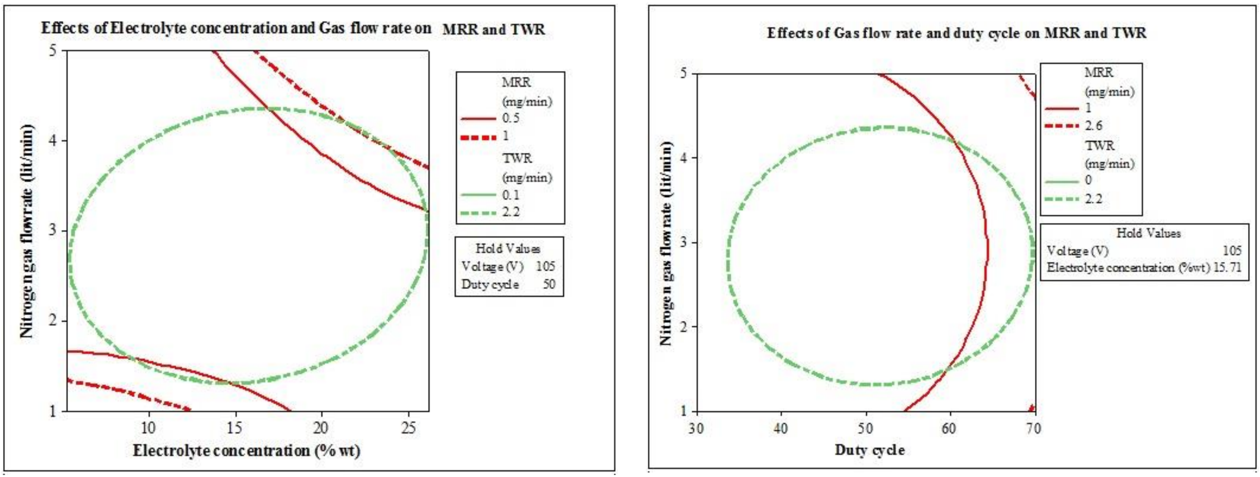


Figure 5. Effects of Nitrogen gas flow rate on MRR and TWR

The experimental results revealed that higher MRR is achieved at 4 lit/min gas flow rate with a reasonable TWR. However, there is a possibility of deposition of nitrides over the machined surface as well as at the tool. In addition, the auxiliary anode material is also possible to deposit over the surface of the tool due to the use of Nitrogen gas.

While using plain aqueous NaOH electrolyte, the deposition of auxiliary anode material into the surface of the tool electrode is not observed. Hence, weight loss was only observed instead of weight gain as observed in Nitrogen gas-assisted machining. Higher electrolyte concentration yields higher MRR of SS316L in μ ECDM. The duty cycle performs better only when it is above 50 with higher electrolyte concentration and gas flow rate of 3-5 lit/min. Maximum MRR of 2.6 mg/min was obtained at 105V, duty cycle of 70, 15.708 wt % of electrolyte and 3 lit/min of Nitrogen gas flow rate. In the plain aqueous NaOH machining, it was 2.4 mg/min at 130V, 50 as duty cycle and 15.708 wt % electrolyte concentration which is 8.33% lesser than nitrogen gas assisted machining. The machined workpiece for both conditions was given in Figure 6.

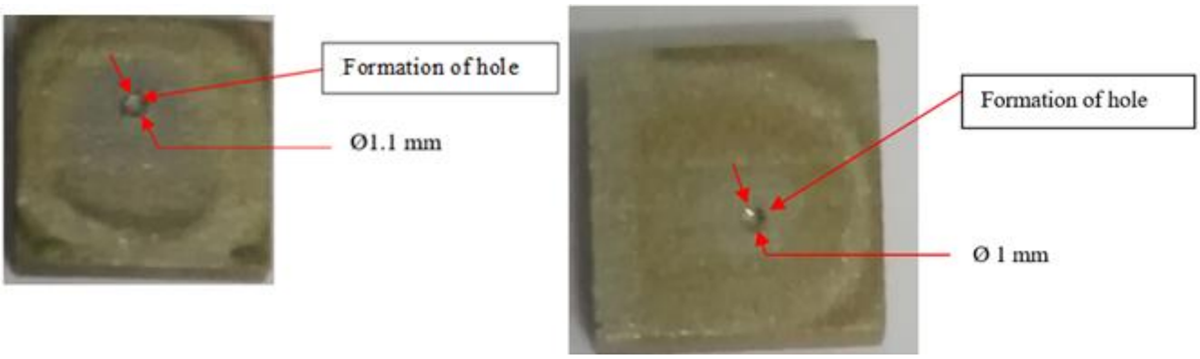
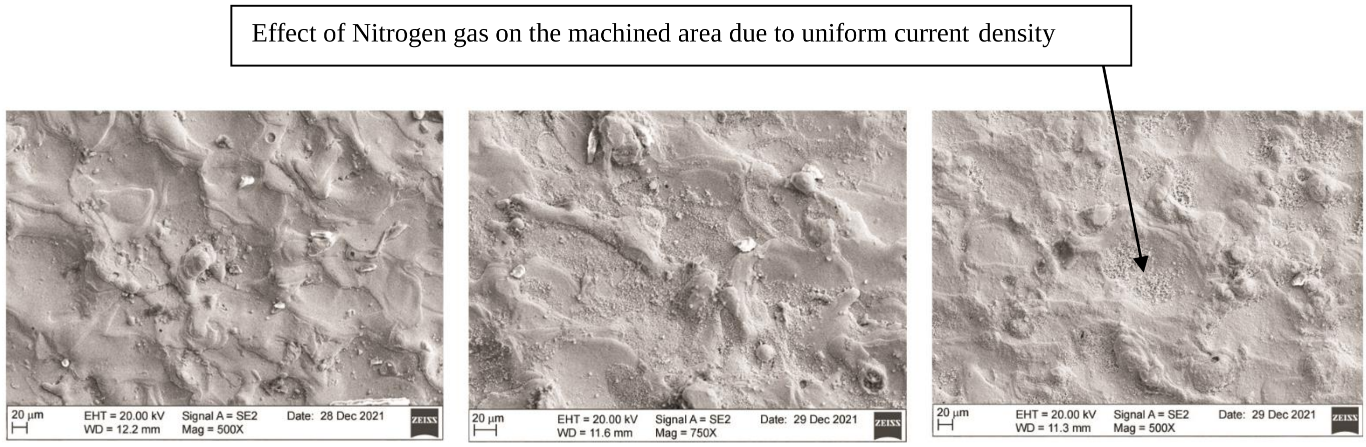


Figure 6. Machined SS316L samples (a) using plain aqueous NaOH (b) using Nitrogen gas assisted aqueous NaOH

Reduction of voltage indicates the reduced cost of machining. At the same working conditions of nitrogen gas assisted machining, it is observed that the TWR was reduced by 33.33 % when compared to the plain aqueous NaOH electrolyte used condition. It is concluded that the performance of µECDM of SS 316 L using Nitrogen gas assisted aqueous NaOH as the electrolyte is better in obtaining high MRR and low TWR with the selected voltage between 100 and 110V, duty cycle above 50, higher electrolyte concentration i.e., 5 to 15 wt % of NaOH and the Nitrogen gas flow rate of 3 to 5 lit/min.

3.5 Microscopic analysis:

The Scanning Electron Microscope (SEM) images of samples is shown in Figure 7. The SEM images inferred that the effect of Nitrogen gas is significant as it produced consistent and uniform of current density across the machining region and hence improved the performance. More amount of surface irregularities is observed in Figure 7 (b) that refers to plain aqueous NaOH electrolyte condition. It could have happened due to instability of gas film at the hydrodynamic regime and also insufficient heat transfer from the generated spark to the workpiece through the gas film. Poor localized metal evaporation/melting have decreased MRR. Figure 7 (c) shows the machined area of nitrogen gas assisted machining, where uniform current density was applied. The reason for observing the better machining is that nitrogen gas has effectively assisted to improve the gas film characteristics by the way of acting as a dielectric medium and providing inert exposure at the machining region resulting in the prevention of heat lost through the air. Obviously, the thermal conductivity of air is higher than Nitrogen gas. The working electrolyte temperature also helped to improve the working domain for achieving better MRR and TWR.

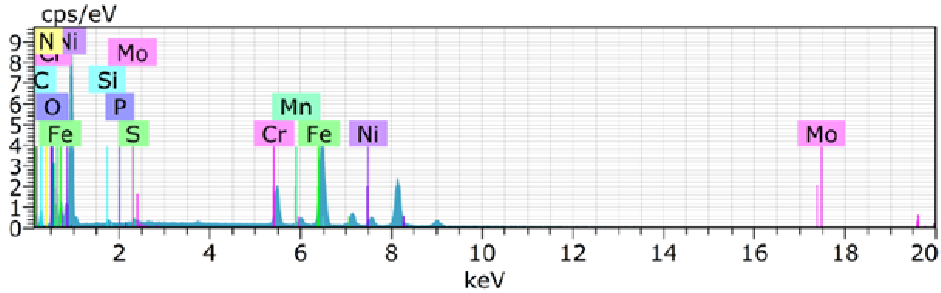


(a) Unmachined SSS 316L

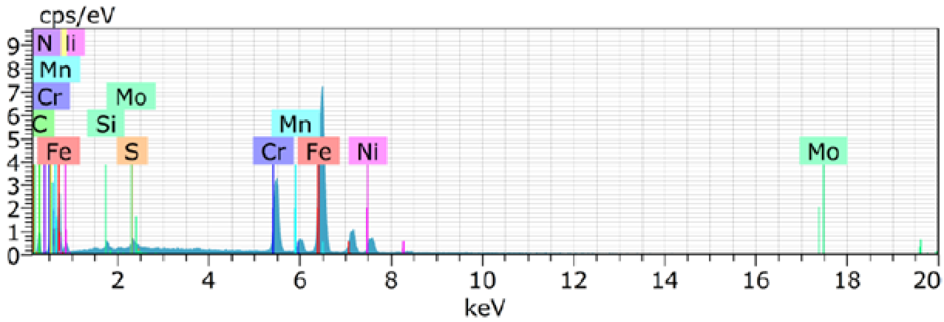
(b) Machined SSS 316L using plain aqueous NaOH electrolyte

(c) Machined SSS 316L using Nitrogen gas assisted aqueous NaOH electrolyte

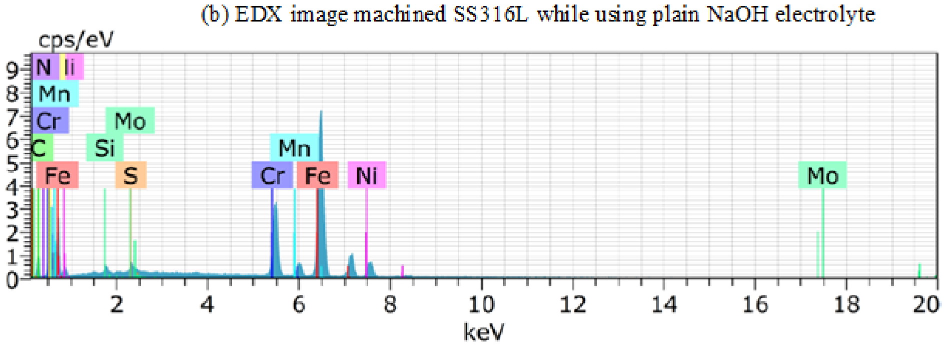
Figure 7. SEM images of machined SS316L samples



(a) EDX image of un-machined SS316L



(b) EDX image machined SS316L while using plain NaOH electrolyte



(c) EDX image machined SS316L while using Nitrogen gas assisted NaOH electrolyte

Figure 8. EDX images of machined SS316L samples

The EDX or EDAX images shown in Figure 6 were captured using the x-ray dispersion technique to identify the elemental composition of materials. The chemical elements of SS316L are shown in Figure 8 (a), while Figure 8 (b) and (c) depict the chemical composition of machined samples. It is understood that the Oxygen and Phosphorus have oxidized due to the chemical reaction taken placed in the machining. Other than this, there is no more absolute change of chemical composition is observed.

3.6 Confirmatory Experiment:

The confirmatory experiments help to assess the consistency of the experimentation. Considering voltage of 120V, duty cycle of 70, NaOH electrolyte concentration of 26.18wt%, experiments were conducted with plain NaOH electrolyte and Nitrogen gas assisted NaOH electrolyte (with additional parameter of flow rate=5 lit/min). The improved performance of µECDM was observed in the modified µECDM setup, where about 10% of MRR is increased, and about 21% of TWR is reduced. Hence the greatness of the modified µECDM experimentation is validated and confirmed for industrial usage.

Table 4. Comparison of performance of µECDM with plain NaOH electrolyte and nitrogen assisted NaOH electrolyte

MRR (mg/min)		TWR (mg/min)	
Plain aqueous NaOH electrolyte	Nitrogen gas assisted aqueous NaOH electrolyte	Plain aqueous NaOH electrolyte	Nitrogen gas assisted aqueous NaOH electrolyte
Machining condition: Voltage=120V, Duty Cycle=70, Electrolyte concentration=26.18 wt%	Machining condition: Voltage=120V, Duty Cycle=70, Electrolyte concentration=26.18 wt%, Nitrogen gas flow rate = 5 lit/minute	Machining condition: Voltage=120V, Duty Cycle=70, Electrolyte concentration=26.18 wt%	Machining condition: Voltage=120V, Duty Cycle=70, Electrolyte concentration=26.18 wt%, Nitrogen gas flow rate = 5 lit/minute
4.72	5.24	1.20	0.95
Improvement in performance of modified µECDM =~10%		Improvement in performance of modified µECDM =~21%	

4. CONCLUSIONS

The experiments were conducted to investigate the effect of Nitrogen gas-assisted aqueous NaOH electrolyte in micro-Electrochemical Discharge machining of Austenitic Stainless Steel Graded 316L. Nitrogen gas is a dielectric gaseous medium that helps to improve the dielectric characteristics of generated gas film between the tool electrode and workpiece and hence this difficult-to-machine material can be machined at lower cost. The identified metal removal mechanism of modified µECDM has localized melting of the workpiece, chemical etching, and thermal erosion. Nitrogen gas improved the current density across the gap by the way of getting the stability of gas film at the Hydrodynamic regime. Nitrogen gas assisted aqueous NaOH has provided the tool electrode weight gaining by the way of deposition of the auxiliary anode metal. In nitrogen assisted µECDM, the maximum MRR of 2.6 mg/min was obtained at 105V, duty cycle 70, 15.708 wt % of electrolyte and 3 lit/min of Nitrogen gas flow rate. The maximum MRR under plain aqueous NaOH was only 2.4 mg/min at 130V, 50 as duty cycle and 15.708 wt% electrolyte concentration which is 8.33 % lower than nitrogen assisted µECDM. It was also observed that the TWR is decreased by 33.33% at the best machining condition of nitrogen gas assisted µECDM. The investigations also reveal that the duty cycle should be higher than 50 for µECDM of steel-based materials. EDX results reveal that the chemical composition of the base material was not affected, except Oxygen and Phosphorous elements. These elements got oxidized during the chemical etching process. Confirmatory experiments conducted at the same machining condition for both cases reveal that about 10% increase of MRR and 21% decrease of TWR can be obtained from Nitrogen gas assisted µECDM. To this end, it is concluded from our investigations that the modified µECDM will be more beneficial to the machining industries.

FUNDING
None

CONFLICT OF INTEREST
None

DATA AVAILABILITY STATEMENT
Data are associated with this research can be obtained from the corresponding author on reasonable request.

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