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MACHINING OF BOROSILICATE GLASS WITH ECDM USING DIFFERENT ABRASIVES

Balwinder Singh[1], R O Vaishya[2], Vikas Sheel[3]

Department of Production & Industrial Engineering, PEC University of Technology, Chandigarh, India

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Abstract - *The specific requirements of advanced materials in advanced industries like nuclear reactor, automobiles, aeronautic have raise the need of advance machining processes which can machine such materials with high material removal rate as well as desired surface quality. Electrochemical discharge machining (ECDM) is one of the hybrid advance machining processes which have potential to machine advance materials with good surface quality desired by Industries. The selection of parameter for higher material removal rate, higher surface finish and minimum tool wear rate is very essential during ECDM. In this present review Paper, a study of the effective Parameters of ECDM has been carried out with their specific role in material removal and surface finish. The optimized range of parameters by different optimizing techniques has been summarized.*

The objective of the present study is to analyse the machining performance of abrasive assisted TW-ECDM using straight polarity to get maximum Material Removal Rate (MRR) and minimum Surface Roughness and analysing the significance of the affecting parameters.

Key Words: Optimization Techniques, Electrochemical Discharge Machining, Material Removal Rate, Surface Roughness.

1. INTRODUCTION

Hybrid machining processes are the current machining methods now a days ruling the industries where precision accuracy and nature of workpiece is the major concern. A number of non-conventional methods are available now a days depending on the application and advantages various different type of workpiece can be machined. Materials can be conductive as well as non-conducting hence depending on their nature we have to select which method will be best suited like conducting materials can be easily and precisely with ECM and EDM and various more methods. But when the material is non-conducting then limited methods are available laser beam machining (LBM), ultra sonic machining(USM), abrasive jet machining(AJM), abrasive water jet machining(AWJM), electron beam machining (EBM), and ion beam machining (IBM), Size and the aspect ratio are some of the few constraints when using these processes. Electro chemical discharge machining (ECDM) then came in picture which can cut non conducting materials like diamond, ruby, Quartz, Pyrex Glass, e-glass ceramics, advanced composites and Fiber reinforced plastics (FRP) etc. the best thing with this method is we can machine with very high precision with very less tool wear but the time consumption is more which can be controlled. Machining is done using the combined principle of ECM and EDM i.e. discharge and chemical etching. Electro chemical discharge machining (ECDM) is said to be a hybrid machining of Electro chemical machining (ECM) and Electro discharge machining (EDM) but actually it is not a hybrid of these two processes as in ECM process current is high and voltage is low but in EDM voltage is high and current is low. Whereas in ECDM even with low current and voltage combination machining can be done. The voltage and current may vary depending on the material and other parameters selected.

Present paper deals with the effect of various process parameters on material removal rate (MRR) and Surface Roughness (SR). There are many process parameters for ECDM but in our present study we consider type of electrolyte, electrolyte concentration and type of abrasive. All the experiments were done keeping the voltage constant at 30V. This level of voltage was considered after analyzing the previous research papers.

2. LITERATURE REVIEW

Kellogg (1950) laid the foundation of the electrochemical discharge machining (ECDM) by studying the anode effects on molten salt. Contact Glow Discharge Electrolysis (CDGE) a new name came into existence (Hickling and Ingram, 1964). Kurafuji and Suda (1968) termed the process as electrical discharge drilling. Tool electrode material and electrolyte composition were discussed in their studies and had demonstrated the drilling of micro holes in glass. Then the another name was given to the process “Discharge machining of non-conductors” by Cook et al. (1973), they stressed that the process reported by earlier researchers was different from ECM and EDM. They also concluded that the drilling rates were a function of micro hole depth. In (1985), Tsuchiya et al. presented a new variant of the process developed by Kurafuji and Suda by using a wire as a tool-electrode. They termed this process *wire electrochemical discharge machining* and showed that glass and various ceramics can be cut using this technique. Much new advancement in the process had been reported for the last three decades. Wuthrich has given some important dates in history of SACE (2012) in his book “Micromachining using Electrochemical Discharge Phenomenon.”

3. SPARK MECHANISM

Electrochemical discharge machining (ECDM) consists of two electrodes having opposite charges connected to a direct current (DC) source of supply. Voltage is supplied across the electrodes dipped in the electrolyte. The area of the anode is 100 times larger the area of cathode. The electrolytes commonly used are strong alkaline solution of sodium hydroxide (NaOH) and potassium hydroxide (KOH). When the voltage is gradually increased, there is the formation of the bubbles on the periphery of the tool electrode. This may be due to the joule heating effect-giving rise to the local temperature or electrochemically formation of bubbles (as cathode attracts hydrogen ions) and their combined effect could also be possible. Hydrogen bubbles are formed at the tool electrode and oxygen bubbles are formed at the auxiliary electrode. When the terminal voltage is increased high enough there is also an increase in the current density. This phenomenon leads to the formation of more bubble and quantity and rate of the occurrence increase with increase the voltage. At the critical voltage the small light emissions could be observed. Such that the machining of the material could be done by sparks. The material has to be placed near the vicinity of the spark region to take its advantage. The distance between the tool and the workpiece should be microns. Wutrich captured some images of spark generation with incremental change in the voltage. Successive steps towards the electrochemical discharge phenomena: (a) 0 V; (b) 7.5 V; (c) 15 V; (d) 40 V. shown in below fig.

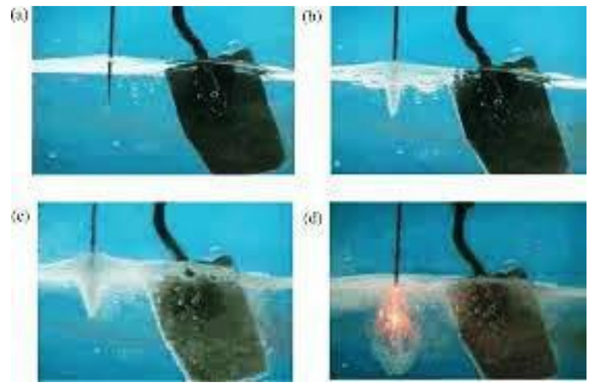

Fig-1: Step wise spark generation

Few researchers had worked on the theoretical model for the occurrence of discharge phenomenon. Basak and Ghosh (1997) calculated the estimation of the critical voltage and the current required to initiate the discharge. Jain et al. (1999) considered each bubble as a valve, when at high electric field the discharge is produced in the form of arc after breakdown of bubble. Another interesting theoretical model based on percolation theory was forwarded by Fascio et al. (2004) for the production of the bubbles by electrical discharge at tool electrode interface and predicted critical parameters involved. Their study highlighted the parameters which played major role in the gas film formation such as voltage, current density and electrical resistance.

4. CHEMICAL REACTIONS

As material removal process in ECDM technique is taking place by thermal heating then followed by chemical etching hence some kind of chemical reactions are also taking place at cathode and anode. During the straight polarity Zinc diffused brass wire was given negative charge i.e. cathode and graphite as anode. When the potential difference is applied across the electrode, gas is evolved and it increases more with the increase in the potential difference. It’s a very complicated process as mechanism is not yet established (Wüthrich, 2009). Hence according to Volmer reaction the hydrogen is evolved as the chemisorption of the water molecules on the free electrode sites M, and M-Hads is denoted as the hydrogen adsorbed on the electrode surface.

$$M + H_2O + e^- \rightleftharpoons M - H_{ads} + OH^-$$

As per the *Heyrovosky reaction:*

$$M - H_{ads} + M + H_2O + e^- \rightarrow 2M + H_2\uparrow + OH^-$$

And as per the *Tafel reaction:*

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$$M - H_{ads} + M - H_{ads} \rightarrow 2M + H_2 \uparrow$$

The hydrogen gas evolved is ejected to the atmosphere. The hydrogen reactions occur when the charge on the wire electrode is negative (cathode) i.e. it has straight polarity. Similarly we can evaluate the oxygen gas reaction on the anode electrode in this case we had taken the graphite electrode. The electrolyte used here are potassium hydroxide (KOH) and NaOH which are highly alkaline solution and the possible reaction occurs is;

$$4\ OH^- \rightarrow O_2\uparrow + 2\ H_2O + 4\ e^-$$

As the alkaline solution (KOH) is dissolved into the solution the potassium ions become mobile. Hence it provides a channel for the current to pass as the solution contains ions of potassium (K^+), hydrogen (H^+) and hydroxide (OH^-).

$$H_2O_{aqueous} \rightarrow H^+ + OH^-$$

$$KOH \rightarrow K^+ + OH^-$$

Similarly, alkaline solution (NaOH) is dissolved into the solution the sodium ions become mobile. Hence it provides a channel for the current to pass as the solution contains ions of potassium (Na^+), hydrogen (H^+) and hydroxide (OH^-).

$$H_2O_{aqueous} \rightarrow H^+ + OH^-$$

$$NaOH \rightarrow Na^+ + OH^-$$

And reaction at zinc diffused wire acting as cathode is given as:

$$Zn \rightarrow Zn^{2+} + 2e^-$$

5. TRAVELLING WIRE ECDM SETUP DETAIL

Figure represents the in house fabricated Travelling Wire ECDM setup. Nylon sheet of thickness 20mm is used in making base of the setup as well as the pulley and pillars. The base of the setup is 122cm long and 8cm wide so as electrolyte chamber wire binding and spool wire holding spool can be mounted properly. In the machining chamber the support on which stepper motor is mounted is also made of 20mm thick nylon sheet. As the wire spool is having weight pillars for wire spool and wire binding height 14cm and diameter 2cm are made of 25mm thick nylon sheet to provide more strength to the setup. An electrical conductive copper bolt of 25mm diameter and 10mm length are used to conduct the regulated DC supply from the DC supply to the wire. Lead screw was machined in house having 1.25 mm pitch and 20 threads per inch. It is 180 mm in length.

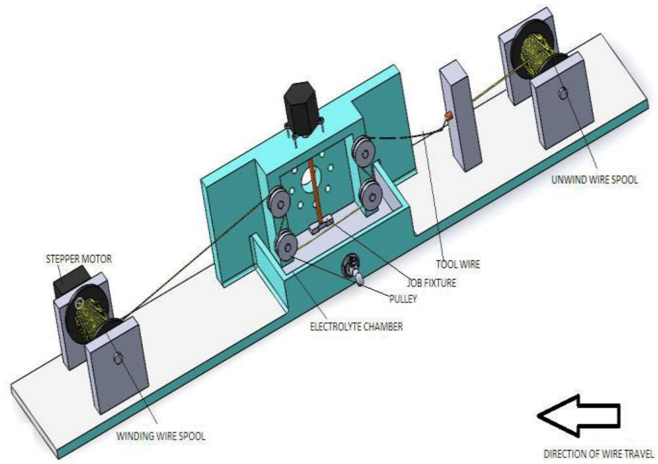

Fig-2: In house fabricated TW-ECDM setup

5.1 Stepper Motors

Two stepper motor NEMA-23 frame size and 10kgcm torque rating are used. It has short-circuit protection for the motor outputs, over-voltage and under-voltage protection and will survive accidental motor disconnects while powered-up.

Motor Features

- Step Angle : 1.8 Degree
- Configuration: 4 or 6 wire stepper motor
- Holding Torque: 10.2kgcm bipolar, 7.2kgcm unipolar
- Rated voltage : 3.3VDC
- Phase current : 2Amp
- Resistance/phase: 1.65E

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- Inductance/Phase : 2.2mH
- Rotor inertia: 275 gcm2
- Detent torque: 0.36kgcm
- Length (L): 51mm
- Weight: 650 grams

Fig-3: Wire winding & workpiece feeding stepper motors

5.2 Wire (Tool Electrode)

In Wire ECDM process wire plays crucial role in machining. Zinc coated brass wire with its high conductive brass core & diffused zinc provides all round performance like high cutting speed, excellent surface finish & better accuracy.

Fig-4: Zinc coated brass wire

5.3 Job fixture

To machine a workpiece, a job fixture was designed to counter the effects of the upward force exerted by the brass wire and to hold the workpiece in place to avoid any lateral and any other unwanted movements.

Fig-5: Job fixture to hold the workpiece

5.4 Regulated DC power supply

In wire ECDM the machining takes place by the regulated DC power supply. The power supply used here has the limits of voltage is 0-80VDC and current between0-15 amp. From the power supply the positive terminal is given to tool wire and negative to the auxiliary graphite electrode making the setup to run on direct polarity.

Fig-6: Regulated DC power supply

5.5 Power supply for stepper motor

To provide power to the stepper motor an industrial switch mode power supply(SMPS) is used, it is same as been used in the desktop computers. The aluminium casing power supply can provide the 24 V and 10 A current. Input voltage required is 230 VAC and 240W power rating. 19VDC was provided to the micro step drives.

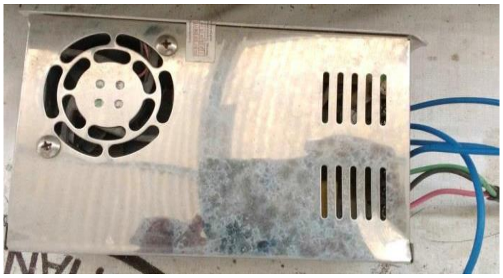

Fig-7: Power Supply for stepper motor

5.6 Breakout board

To provide the communication between the CNC software MACH-3(demo version) and the micro stepping drives, a parallel port buffered breakout board (R M C S - 2 4 0 1) is used. A DB25 female parallel port connector is used to provide the signals from the CNC to board.

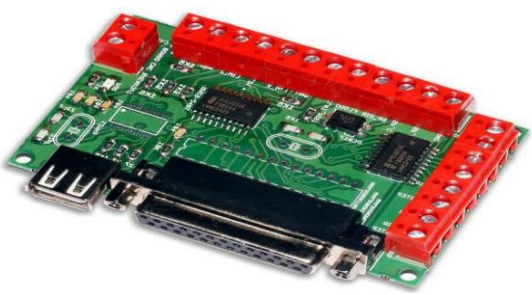

Fig-8: Breakout board used during the process.

5.7 Micro stepping Device:

To provide smooth and quiet operation at lower speeds micro stepping (figure 10) drive was used. As there were two stepper motors, two micro-steppers were provided. The 6400 steps per revolution were selected, the wire feed was given 1 mm/min as it was constant throughout the process and wire feed rate was fixed at 3m/min and 10,000 steps per revolution.

Fig-9: Micro Stepping device

6. WORKPIECE DETAIL

Borosilicate glass also known as pyrex glass by manufacturers of thickness 4mm is used. Borosilicate glass is used on the basis of its appreciable properties discussed below

Table 6.1: Chemical Composition

Composition	(percent approx.)
SiO_2	80.6%
B_2O_3	13.0%
Na_2O	4.0%
$A1_2O_3$	2.3%

Table 6.2: Physical Properties

Coeff. of Exp.	$32.5x10^{-7}$ cm/cm/°C
Strain Point	510°C
Anneal Point	560°C
Soften Point	821°C
Density	2.23 g/cm^3
Young's Modulus	6.4 x 10^3 Kg/mm^2
Refract. Index	1.474 @ Sodium D Line
Temp. Limits	490°C (Extreme Service)
	230°C (Normal Service)
Max. Thermal Shock	160°C

7. EXPERIMENTATION

In the present study three variable parameters type of electrolyte, concentration of electrolyte, type of abrasive and all other parameters are set constant. Machining is done on direct polarity keeping wire feed rate(3m/min.) and Voltage 30V constant. Response parameters are taken as material removal rate and Surface Roughness. Some of the parameters are taken as variable parameters to examine their effects and others are taken as constant based on the previous literature.

NaOH, KOH and $NaNO_3$ are taken as the electrolytes for present study. To avoid the wastage and get the optimum results making the system cost effective concentration of the electrolyte is taken at three levels i.e. 15%, 20% and 25% by weight concentration.

Table 7.1: Symbolic representation of input parameters and their levels

Symbol	Process Parameter	Level-1	Level-2	Level-3
A	Type of Electrolyte	KOH	NaOH	$NaNO_3$
B	Electrolyte Concentration	15%	20%	25%
C	Type of Abrasive	Alumina	Silica	Graphite

As discussed above for our experimentation we have 3 factors at 3 level, in that case total experiments become 27 to perform. But because of frequently breakdown of wire in our setup that much experiments can be very tough to perform that's why L_9 partional orthogonal array is used. It will reduce the number of experiments to 9 from 27 but the results will be same, this is why it is called as optimization technique. In this design, we are available with 9 horizontal rows and 3 columns that means total of 9 experiments to be performed. Interactions are taken on the basis of degree of freedom available.

All experiments are carried out by the same procedure and at constant wire feed rate and 30V voltage as discussed, the following data for various response parameters are obtained. Each set of parameter is taken and experiment is performed. Like for experiment no.1 potassium hydroxide (KOH) electrolyte by 15% weight concentration and alumina ($Al_2 O_3$) abrasive are taken as input parameters and corresponding to the input parameter the response parameters Surface Roughness (SR) and MRR examined. First 3 experiments are done using KOH electrolyte with varying electrolyte concentration and abrasive are performed. Similarly the next 6 experiments are performed and response parameter values are noted. Each time after experiment electrolyte chamber is cleaned, fresh electrolyte is prepared and mixed with the subsequent abrasive of different type as been set in the L9 OA. Machined surface of workpiece is almost same after all the experiments, we can't differentiate it with naked eyes. Following is the image of workpiece after machining

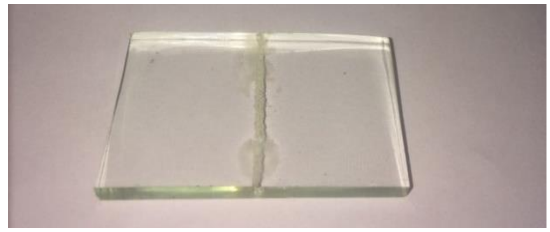

Fig-10: Machined Workpiece after Experiment

Table 7.2: L_9 OA for Surface Roughness &MRR

	Control Factors			**Response Factors**	
ExptNo.	**A**	**B**	**C**	**SR (in μm)**	**MRR (g/min)**
1	1	1	1	6.02	0.0110
2	1	2	2	6.35	0.0309
3	1	3	3	7.22	0.0377
4	2	1	2	5.53	0.0053
5	2	2	3	3.39	0.0136
6	2	3	1	2.28	0.0334
7	3	1	3	1.89	0.0037
8	3	2	1	2.59	0.0123
9	3	3	2	2.23	.0064

Surface Roughness Observations were taken with the help of Mitutoyo Surface Roughness Tester (SJ400) and MRR was calculated with the help of Denver SI 234 Weight Measuring Machine Also weight measuring machine accuracy upto four decimal points is used to measure the electrolyte and abrasive weights. Maximum weight carrying capacity of the machine used here is 230gm.

8. RESULTS

8.1 Effect of input parameters on Surface Roughness (SR)

Plots are drawn using Minitab software for main effects plots and interaction plots for means. From main effect plot of means, we can conclude that experiment result for SR gives optimum values at KOH electrolyte, at 15% concentration of electrolyte, Silica abrasive and at 30V voltage which was kept constant.

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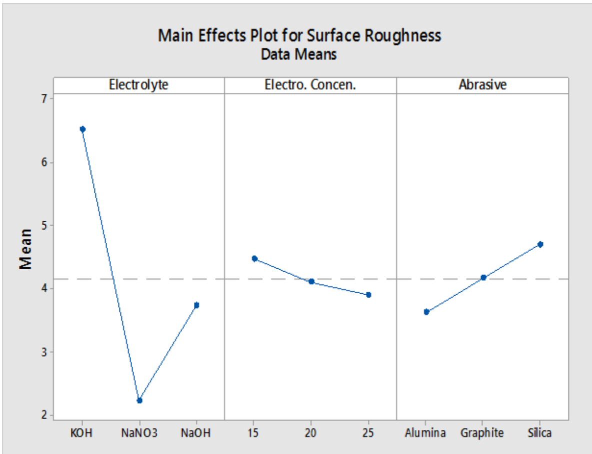

Fig-11: Main effect plot for means of SR

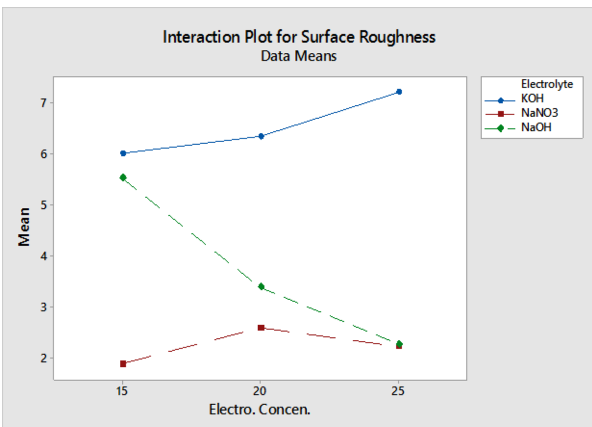

Fig-12: Interaction plot for SR taking electrolyte and it's concentration

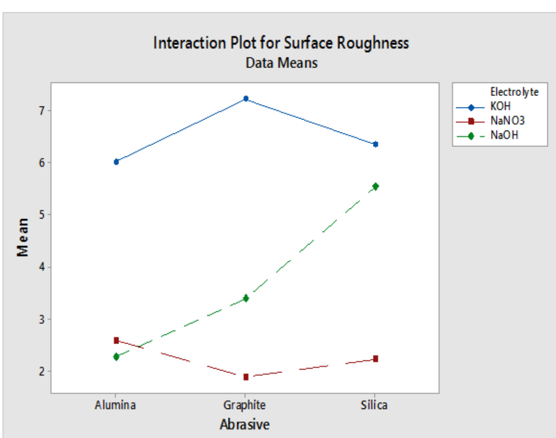

Fig-13: Interaction plot for SR taking electrolyte and abrasive

From the main effect plots it can be clearly concluded that the type of Electrolyte is critical for Surface Roughness as it shows steep slopes. The other parameters i.e Concentration of electrolyte and type of abrasive are not much significant for Surface Roughness

8.2 Effect of input parameters on MRR

From main effect plot of means, we can conclude that experiment result for MRR gives optimum values at KOH electrolyte, at 25% concentration of electrolyte, alumina abrasive.

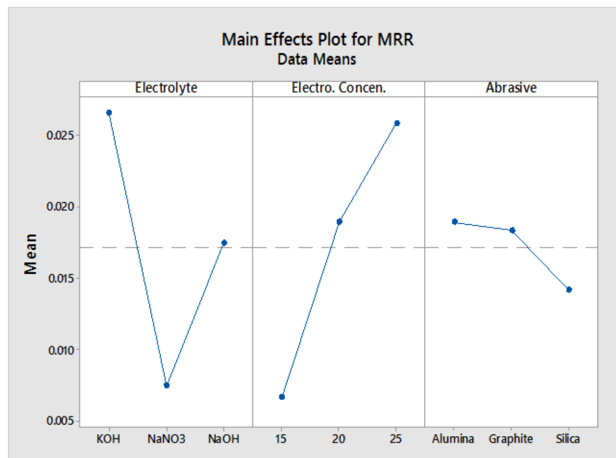

Fig-14: Main effect plot of means for MRR

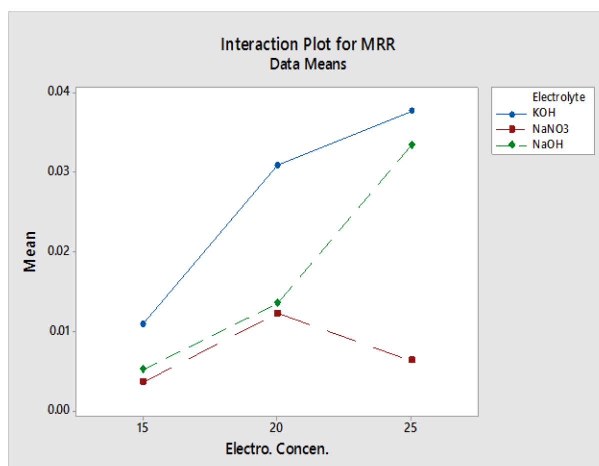

Fig-15: Interaction plot for MRR considering electrolyte and its concentration

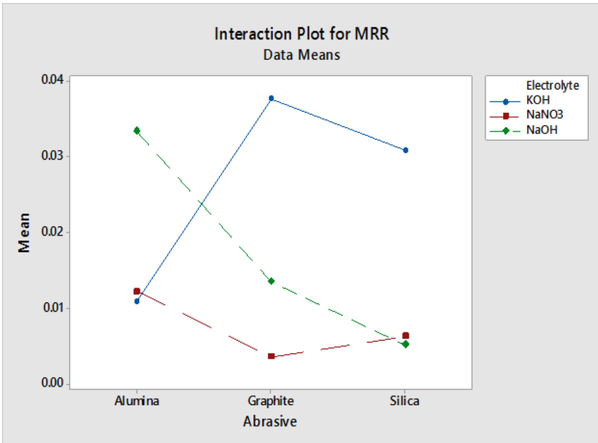

Fig-16: Interaction plot for MRR considering electrolyte and Abrasive

From the main effect plots it can be clearly concluded that the type of Electrolyte and it's concentration is critical for Material Removal Rate (MRR) as it shows steep slopes. The other parameters i.e type of abrasive is not much significant for MRR

9. CONCLUSIONS

1. Surface Roughness (SR) is seen more in case of KOH and NaOH as compared to $NaNO_3$ electrolyte. Surface Roughness is minimum at 25% electrolyte concentration, $NaNO_3$ Electrolyte and with alumina abrasive.
2. The main parameter for SR is type of Electrolyte
3. For MRR optimum parameters is KOH, 25% Electrolyte concentration and Alumina abrasive.
4. MRR is higher when KOH electrolyte is used and Surface Finish is higher when $NaNO_3$ electrolyte is used.
5. With NaOH smooth cutting is obtain with average MRR
6. Electrolyte concentration increases material removal rate (MRR).
7. As concentration of abrasive is increases material removal rate (MRR) increases.
8. Abrasive addition in electrolyte is increasing the critical voltage of spark generation.
9. The main parameters in MRR are type of Electrolyte and it's concentration.
10. Alumina abrasive shows the maximum MRR and minimum SR.

The higher MRR and Lower SR are desired values of every machining process. From the above plots, it can be clearly concluded that alumina (Al_2O_3) holds good qualities for maximizes the Material Removal Rate and minimizes the Surface Roughness as compared with graphite and silica abrasives.

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