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Micromachining with ECDM: Research Potentials and Experimental Investigations

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Abstract**—**Electro Chemical Discharge Machining (ECDM) is an emerging hybrid machining process used in precision machining of hard and brittle non-conducting materials. The present paper gives a critical review on materials machined by ECDM under the prevailing machining conditions; capability indicators of the process are reported. Some results obtained while performing experiments in micro-channeling on soda lime glass using ECDM are also presented. In these experiments, Tool Wear (TW) and Material Removal (MR) were studied using design of experiments and L–4 orthogonal array.Experimental results showed that the applied voltage was the most influencing parameter in both MR and TW studies. Field emission scanning electron microscopy (FESEM) results obtained on the microchannels confirmed the presence of micro-cracks, primarily responsible for MR. Chemical etching was also seen along the edges. The Energy dispersive spectroscopy (EDS) results were used to detect the elements present in the debris and specimens.

Keywords**—**ECDM, applied-voltage, FESEM, EDS.

I. Introduction And Review Of Researches

ELECTRO-CHEMICAL Discharge Machining (ECDM) [1], a hybrid machining process of Electric Discharge machining (EDM) and Electro-Chemical Machining (ECM) process and are mainly used for micro-machining and scribing hard and brittle non-conductive materials such as glass (mainly pyrex, plexi and optical), ceramic, refractory bricks, quartz and composite materials. The schematic of the basic ECDM process is shown in Fig. 1.

Various researchers have put forth explanations based on their studies and the most acceptable mechanism of material removal is due to the thermal mode primarily by melting and vaporization and partially by chemical mode through etching. The workpiece is heated by fraction of the spark energy which raises the local spot temperature to a very high value, sufficient for melting and vaporization.

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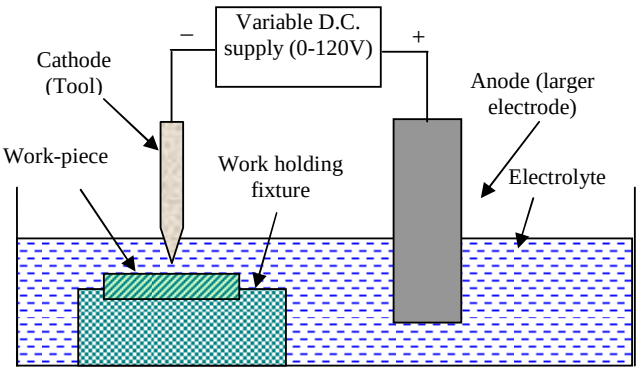

Fig. 1 Schematic of the ECDM set-up

Wuthrich and Fascio [2] have reported extensive studies on glass and ceramic regarding material removal rate (MRR) and tool wear rate (TWR). The main challenge discussed was in controlling the gas-film in the machining zone, its stability and dynamics. While drilling in glass, it was reported that MRR and TWR increase with applied DC voltage and electrolyte temperature. Depending upon the tool and work-piece material, the commonly used electrolytes [2] are NaOH, NaCl, $NaNO_3$, KOH, $NaNO_3$, HCL, H_2SO_4, NaF etc.

Yang et al. [3] have defined ECDM to be a high temperature etching process which depends on the type of the electrolyte used. Jain et al. [4] have used alumina glass composite ceramic material and found that the machining rate is greatly affected by the porosity of samples. The material removal occurs by attacks at the grain boundary mostly due to the etching process. Liu et al. [5] have reported that the craters formed in ECDM process are almost same as those formed in the EDM process, along with some re-cast effects, which are mainly due to the sparking action. Spalling is the major material removal mechanism as per the reported findings by Gautam and Jain. [14].

Much of the work in ECDM has been concentrated on glass (pyrex and borosilicate), which has useful properties and applications in industrial, defense, medical and electronic industries. Quartz, alumina-glass ceramic and composites are other materials that have been attempted earlier. A critical summary on review of the ECDM process indicating commonly used materials, machining conditions, capability indicators and major findings are presented in Table I.

TABLE I
MAJOR FINDINGS ON MATERIALS AND MACHINING CONDITIONS USED IN ECDM

Material (Glass)	Machining Condition	Capability indicator	Process variant used			Major findings	Reported By
			Micro-drilling	3-D	TW-ECDM		
Glass (Pyrex)	Voltage : 20-45 (V) Pulse : 0-80 Elec. Con. : 5-40 (wt%)	Resistance change, Current Pulse counts (0-75)	√			V_c =38, for NaOH at 25º C and 30%Conc.	Fascio et al.[6]
Glass (Pyrex)	Electrolyte, KOH Voltage, >30 (V) Current, 10 (A)	Mean current : 95-142 (mA), Depth : 100-450 (µm), Gas films	√			Hole dia 470-492 µm	Cheng et al. [7]
Glass (soda-lime and pyrex)	Electrolyte (NaOH/KOH) Elec. Con. : 20-40 (wt%) Pulse 'V' variation. Work = 150 µm thick	Contact force (mN), M/c time : 500-2000 (S)	√	√		Hole dia: 30 µm, Channels : 40-46 (µm) width R_a : 0.1-0.195 (µm)	Cao Xuan et al. [8]
Glass (Pyrex-wafers)	Electrolyte: KOH: 25% Electrode: Cu, Graphite Current: 10 (A)	Frequency and duty cycle of voltage pulse, MRR in micro drill-ing upto: Ø60 µm	√		√	For less thermal damages, high frequency + low duty cycle ratio preferred	Kim et al. [9]
Glass (Pyrex)	Abrasive conc.: 0-300,g/l Slit grits: 10-60, µm Power frequency: 30-100, Hz	Slit expansion 0.024 mm, SR: 0.84-3.5 (μR_a) MRR : 0.03-0.09 (mg/min)			√	Small grit size abrasive reduces S.R., and refines micro-cracks.	Yang et al. [10]
Glass (soda-lime and Borosilicate)	Voltage: 0-80 (V) Elec. Con.: 20-35 (wt%)	Overcut, Penetration, MRR	√			Relationship in supply 'V' to penetration & 'V' to overcut developed.	Jain et al.[11]
Glass (soda-lime, Alumina)	Elec.Con.:10-60(wt%) Duty factor: 60-80 Energy partition: 0.2-0.9 (R_w)	In soda-lime, MRR increases upto 30% Elec. Con.	√			MRR increases due to increase in R_w in both glasses	Bhondwe et al. [12]
Glass Borosilicate Alumina glass	Voltage: 40-70 (V) Temperature: 40-70 (ºC)	Using MRR, M/c depth, equations in Response surface were generated	√			Abrasive coated tools have shown improved performance	Jain et al. [13]
Glass (Borosilicate)	Voltage, Current Elec. Con., Temperature	M/c. time, Hole expansion, Surface finish	√			MRR=1.5 mg/min S.R=0.08 μR_a	Yang et al. [3]
Borosilicate glass and Quartz	Tool rotation (20 rpm) M/c depth : 0.5-3.0 (mm) M/c Time: 1-6 (min)	M/c rate upto 0.6 mm/min, M/c depth : 0.5 to 1.2 (mm)	√			MRR improved using rotational tool. Thermal and spalling effects noticed.	Gautam and Jain [14]
Alumina and Quartz	Voltage: 50-70 (V) Temperature: 35-80, ºC Electrolyte (type)	MR : 122.7 (mg) in 70 (min), Maximum M/c depth : 1.35 (mm)	√			Temperature found to have significant effect	Jain et al. [15]
Alumina ceramic	Effect of glass content: 0-20 (wt%) Porosity: 0-30 (wt%)	MR : 40-110 (mg) M/c depth : 0.2-2 (mm)	√			The governing factor for MR and M/c depth in ceramics is Porosity	Jain et al. [16]
Alumina Ceramic	Voltage: 70-90 (V) Elec. Con.:20-30, wt% Electrolyte type: NaOH, NaNo3, NaCl Tool tip geometry	Overcut = 0.33-0.56 (mm) for taper side wall, straight side wall and curvature tools	√			Most effective combination for high MRR and accuracy were 80V and 25% NaOH	Bhattacharya et al. [17]
Alumina ceramic, optical glass and quartz	Voltage: 45-90 (V) Frequency : 100-1000 (Hz)	MRR, Voltage and Pulse Current response : 3.8-27 (A)			√	MRR of 0.06mm^3/min for alumina ceramic with R_a = 3.5 µm	Peng et al. [18]
Material (Glass)	Machining Condition	Capability indicator	Process variant used			Major findings	Reported By
			Micro-drilling	3-D	TW-		

					ECDM		
MMC (aluminum alloy-359, 20% Sic)	Current: 0.5-5 (A) Voltage: 20-120 (V) Pulse duration : 4-400 (µs)	Current/Voltage Waveforms and XRD	√			Developed models and found capable of predicting the V_{bk} range as : 26-34 (V)	Liu et al. [5]
Kevlar fiber epoxy, glass fiber epoxy	Voltage: 65-80 (V) Electrolytic- conductance: 0.16-0.18 (S, mhocm-1)	MRR found to be >10 mg/min at 0.19 (S)	√			MRR increases with rise in inductance and lowers with rise in tool dia	Tandon et al. [19]
Epoxy glass + Fiber composite	Voltage: 55-70 V Elec. Con. : 65-80, wt% Anode to cathode gap : 70-200 (mm)	MRR : 1-2.9 (mg/min), Dia: 400 µm, 1 mm deep holes made	√			MR is maximum with high V and moderate Elec. Con.	Manna And Narang [20]

Legend : MRR = Material removal rate, MR = Material removal, TWECDM: Travelling wire electro chemical discharge machining, TWR = Tool wear rate, TW = Tool wear, M/c = Machining, Dia = diameter, V = Voltage, V_c = Critical Voltage, g/l = grams/litre, V_{bk} = Breakdown Voltage, A = Ampere, Hz = Hertz, Elec. Con. = Electrolyte concentration, mm = millimeter, SR = Surface roughness, mN = 10^{-3} Newton, μR_a =Roughness average in microns, R_w = Energy partition, MMC = Metal matrix composite, SiC = Silicon carbide, , S= seconds, XRD = X-Ray diffraction.

II. Microchanneling on Soda-Lime Glass

In the present case study, experiments were conducted on 1.6 mm thick soda-lime glass plates whose elemental composition is as indicated in TABLE II, using NaOH as the electrolyte solution. A vertical spindle milling machine (make : HMT) along with a fabricated experimental set-up was used in the experimentation. The tool used was made of stainless steel as shown in Fig. 2 (diameter 0.7 mm). The auto feed motions of the machine were used for making the micro-channels. The obtained dimensions were in the range of length 10 to 15 mms, width 0.8 to 1mm and depth 0.1 to 0.2 mm. In carefully planned experiments, one does not need to experiment for all variables at all conditions, instead, by applying the design of experiment approach, it is possible to obtain the same results along with interaction effects. In the present experimentations, Taguchi's standard L-4 orthogonal array (TABLE III) has been used. The experimental parameters and levels were chosen from the trial experiments.

TABLE II
COMPOSITION OF SODALIME WORKPIECE

Element	Wt%	At%
CK	34.20	48.96
OK	23.62	25.39
NaK	08.51	06.36
MgK	01.69	01.20
AlK	00.65	00.42
SiK	23.68	14.50
KK	00.61	00.27
CaK	06.14	02.63

In the study, two levels of applied voltage were taken, at two different electrolytic concentrations and feed rates. The parametric conditions, variables and constant parameters maintained in the experimentation process are shown in Table IV.

Fig. 2 Stainless Steel tool (diameter : 0.7mm)

TABLE III
L-4 ORTHOGONAL ARRAY

Trial No.	Parameters		
	A	B	C
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1

A = Applied voltage, B = Electrolyte concentration, C = Work feed rate

TABLE IV
PARAMETRIC VALUES

	Parameters	Units	Terminology	Level-1	Level-2
Variable	Applied voltage	V	A	80	100
	Electrolyte concentration	g/l	B	50	90
	Work feed rate	mm/min	C	6	15
Constant	Parameters	Units		Values	
	Electric current	A		10	
	Current flow (time)	Min		04	
	Electrode ratio (cathode to anode)	cross-section area ratio		1:30	

III. STUDIES ON MATERIAL REMOVAL

The material removed was calculated by measuring the difference in the wokpiece weights on a well calibrated digital weighing machine (model: AUW220 D, make: 'SHIMADZU', least count: 0.01 mg). Workpieces were weighed before and after the experiment, after removing carbon layers with thorough cleaning. The total of factors and average effects [21] are calculated and presented in Table V. The analysis of variance (ANOVA) was performed on the experimentally obtained data and the corresponding results ar presented in TABLE VI. It is observed that amongst the influencing parameters in the studies performed on MR process (TABLE VI), the applied voltage contributes the maximum (94.078%), mainly due to the increased sparking and corresponding thermal energy liberated. This is followed by electrolyte concentration (3.79%) and the feed-rate (2.13%).

TABLE V
AVERAGE VALUES AND EFFECTS IN MR STUDIES

Trial No	Average MR (mg)	Factors	Total of Factors	Factors	Average effects
1	0.59	A_1	2.785	A_1'	1.3925
2	0.52	A_2	2.225	A_2'	1.1125
3	2.195	B_1	2.295	B_1'	1.1475
4	1.705	B_2	2.715	B_2'	1.3575
		C_1	1.11	C_1'	0.555
		C_2	3.90	C_2'	1.95

TABLE VI
ANOVA FOR THE MR STUDIES

Factor	f	S	V	P (%)
A	1	1.9460	1.9460	94.078
B	1	0.078	0.0784	3.7901
C	1	0.044	0.0441	2.1319
Error	0	0		
Total	3	2.068		
Where F = Degree of freedom, S = Sum of squares, V = Variance, P = Percent influence				

The Fig. 3 reveals that MR occurs marginally more at the lower level of applied voltage (80V). At the second level (100V), MR dips down due to steadily increasing influence of chemical effect of the electrolyte. In case of the electrolyte concentration, at the higher level of concentration, more MR takes place mainly due to the chemical etching effect. The higher feed plays a smaller role in the MR and it is observed that the higher feed rate has relatively more influence on MR. It may be attributed to the fact that it gives more space to the gasses and bubbles to escape freely, thereby allowing a more stable film and sparking.

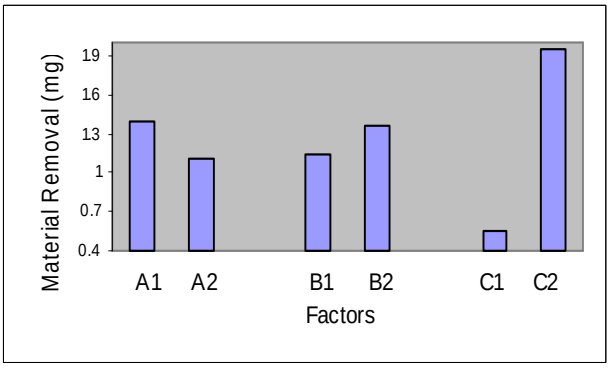

Fig. 3 Average MR at the two parameteric levels
(A = applied voltage, B = electrolyte concentration, C = work feed)

IV. STUDIES ON TOOL WEAR

The tool wear was calculated by measuring the difference in the tool weights on the same digital weighing machine as discussed earlier. Tool weights were measured before and after the experiments, after thorough cleaning. A typical worn out tool is presented in Fig. 4. The total of factors and average effects were calculated as per the standard L-4 orthogonal array calculations [21] and are shown in TABLE VII. In the studies performed on TW process, the applied voltage contributes the maximum (98.674%) followed by electrolyte concentration and the feed-rate (0.663 % each) on tool wear as observed from the ANOVA results as shown in TABLE VIII.

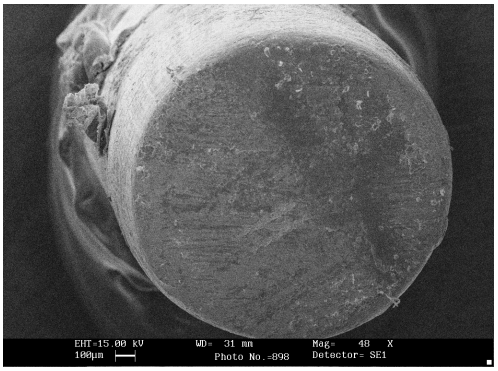

Fig. 4 SEM Micrograph of the worn tool

TABLE VII
AVERAGE VALUES AND FACTORIAL EFFECTS IN TW STUDY

Trial No	Average MR (mg)	Factors	Total of factors	Factors	Average effects
1	0.35	A1	0.725	A1'	0.363
2	0.38	A2	0.42	A2'	0.21
3	0.21	B1	0.56	B1'	0.28
4	0.21	B2	0.585	B2'	0.293
		C1	0.56	C1'	0.28
		C2	2.430	C2'	0.293

The graph in Fig. 5 shows that TW occurs marginally more at the first level of applied voltage. At the second level (100V), it dips down due to the additional influence of chemical effect of the electrolyte. At the higher level of electrolyte concentration, the chemical effect progresses. The higher feed rate has a marginal higher effect on tool wear as it allows space for gases to escape and leads towards a stable sparking process.

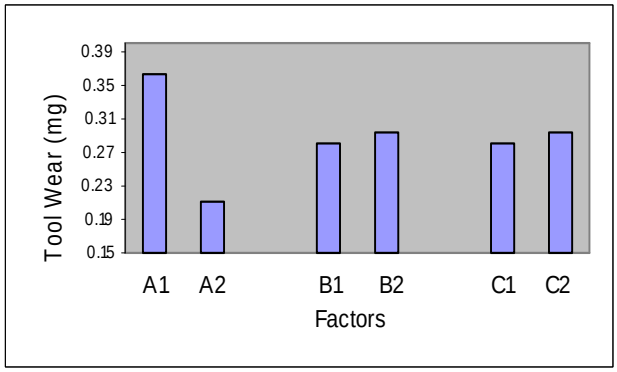

Fig. 5 Average TW at the two parametric levels
(A=applied voltage, B=electrolyte concentration, C=work feed)

TABLE VIII
ANOVA FOR THE TW STUDY

Factor	F	S	V	P (%)
A	1	0.0233	0.0232	98.674
B	1	0.0002	0.0002	0.663
C	1	0.0002	0.0002	0.663
Error	0	1.7E-16		
Total	3	0.0236		

Where F=Degree of freedom, S=Sum of squares,
V = Variance, P=Percent influence

V. INVESTIGATIONS THROUGH FESEM

A macro view of the fabricated micro-channels on glass is shown in Fig. 6. The typical FESEM micrograph of the channel and debris are shown in Fig. 7 and Fig. 8 respectively. The microcracks and craters are seen in the micrograph of the channel (Fig. 7), which are due to the thermal mode of material removal during the sparking process. Some bright edges are visible which are primarily due to the etching effect of the chemical, which are more prominently observed towards the edges at the grain boundaries where etching is predominant.

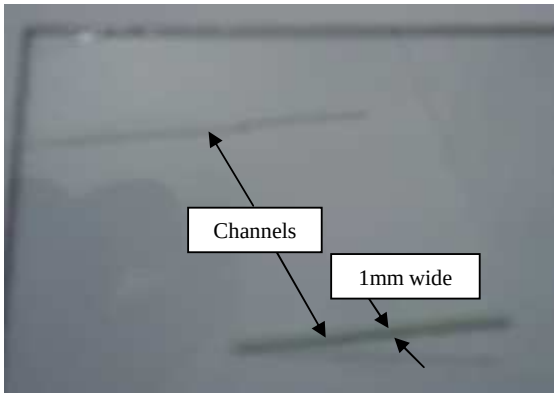

Fig. 6 Channels on glass

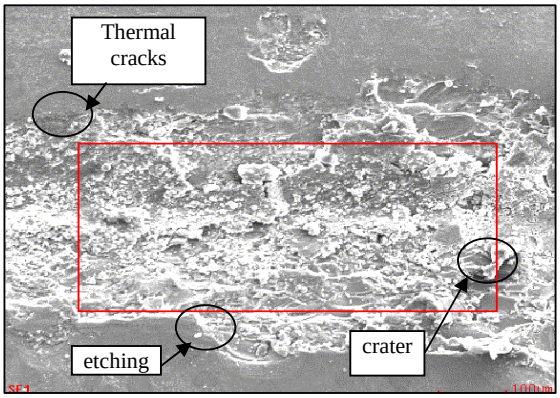

Fig. 7 FESEM micrograph of channel

After the experimentation, the electrolyte used was collected and allowed to settle. The micro-debris was carefully filtered out and dried. The EDS was carried out on these powdered debris and microchannels obtained were also subjected to EDS.

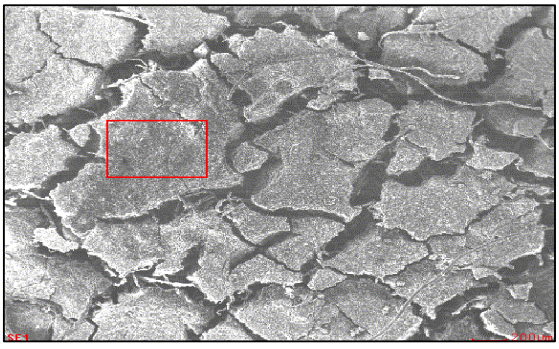

Fig. 8 FESEM micrograph of debris

The composition of standard sodalime glass specimen was checked (TABLE II) and elements were compared with the detected EDS elements from the debris (TABLE IX). The

percentage of various elements detected differ due to the subsequent chemical reaction it forms with the tool and electrolyte during the ECDM process. Apart from the elements present in glass and electrolyte, 'Fe' was detected owing to the reaction of the tool-material and its debris due to the tool-wear.

TABLE IX
ELEMENTAL (EDS) COMPOSITION OF DEBRIS [22]

Element	*Wt%*	*At%*
CK	31.61	46.00
OK	31.24	34.13
NaK	04.56	03.46
MgK	05.81	04.18
AlK	01.73	01.12
SiK	02.31	01.44
KK	00.57	00.26
CaK	20.09	08.76
FeK	02.08	00.65

VI. CONCLUSION

The paper presents a review on materials and processing conditions in ECDM alongwith the micro-machining results obtained while making microchannels (length : 10 to 15 mms, width : 0.8 to 1mm and depth : 0.1 to 0.2 mm). An extensive reliew of the relevant literature has been presented. The review reveals, many researchers have attempted primarily glass as the work material, however, there is hardly any resemblance in the relevant conditions and hence results. No reliable theory on the mechanism of material removal has been accepted in general.

On further analysis of the experimental results through design of experiments, it was found that all the selected process parameters were significant. The applied voltage was found to be the most influencing parameter. The FESEM results give useful inputs on failure modes. Small composition of Fe was seen as a result of tool-wear.

Finer analysis of the chemical compounds formed and the use of higher level O.A. with more parameters can further yield more detailed and insight results to supplement the initial findings reported herein.

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