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Effect of Electrode Shape and Rotation on Quartz with ECDM

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*Abstra*ct: The Electrochemical discharge Machining (ECDM)is non conventional hybrid machining process, which is used for nonconductive material like glass, composite, quartz for micro machining in aerospace, medical, agriculture, optical. electronics applications. High geometrical accuracy and surface finish is the major benefit of machining process. Tool electrode rotation with inter electrode gap, voltage and electrolyte (potassium hydroxide) concentration with three level each for improving the performance of material removal rate as well as overcut. A Taguchi analysis is done on micromachining on quartz material. It is observed that voltage and inter electrode gap in combination increase the efficiency of machining.

Keywords : Taguchi, Electrochemical discharge machining, Electro discharge machining

1.Introduction

Recent progresses made in the field of aviation, automobile, medical, miniature manufacturing and others have created more and more needs for parts with small and micro-size holes in extremely hard and tough materials, such as the holes of fuel injection nozzles with high accuracy requirement, sharp edges without burrs, and the small diameter in the range of 0.4–0.8 mm.

The history of EDM Machining Techniques goes as far back as 1770, when English chemist Joseph Priestly discovered the erosive effect of electrical discharges or sparks. The EDM process was invented by two Russian scientists, Dr. B.R. Lazarenko and Dr. N.I. Lazarenko in 1943. The spark generator used in 1943, known as the Lazarenko circuit, has been employed over many years in power supplies for EDM machines and proved to be used in many current applications. The Lazarenko EDM system uses resistance capacitance type of power supply, which was widely used at the EDM machine in the 1950's and later served as the model for successive development in EDM. Further developments in the 1960's of pulse and solid state generators reduced previous problems with weak electrode as well as the inventions of orbiting systems. In the 1970's the number of electrodes is reduced to create cavities. Finally, in the 1980's a computer numerical controlled (CNC) EDM was introduced

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in USA. Sushil Kumar Choudhary et al.,2014, concluded Vibration, rotary and vibro-rotary mechanism makes the equipment simple and increases the material removal rate, provide better surface finish ejection from work piece. Better circulation of dielectric fluid and debris removal from work piece

The plasma implodes under the pressure imposed by the surrounding dielectric. Consequently, the molten metal pool is strongly sucked up into the dielectric, leaving a small crater at the workpiece surface.

The EDM-end milling has 14.4 times higher processing efficiency than traditional EDM. For low feed rate, material removal mechanism is converted to pure micro-ECM when the thickness of layer dissolved by electrochemical reaction is higher than the preset layer depth. In this situation, the material is entirely removed through dissolution [1].

Due to the relatively high conductivity of hybrid electrolyte, chemical etching has occurred simultaneously during the electrical discharge process machining [2] The MRR was found to increase with an increase of aspect ratio of disk electrode, at all parametric settings. This is attributed to the fact that larger aspect ratio of disk electrode has larger frontal thickness, and thus an increase in the electric field density. Silicon powder additives of finer particle size resulted in increased MRR. With the addition of powder additives into dielectric fluid, spark gap increases, resulting in wide discharge channel. Thus, finer silicon powder particles get energized and traverse in a zig-zag fashion, forms cluster and bridges the spark gap between tool and work facilitates the increase in discharging frequency, and hence enhances the MRR [3].

Electrochemical discharge machining (ECDM) is an advanced hybrid machining process comprising the techniques of electrochemical machining (ECM) and electro discharge machining (EDM). The process is also referred to as electrochemical spark machining (ECSM) process. The process is important since it can support a variety of materials including metals, ceramics, composites, alumina, glass, etc. The process has possible potential usage in the following areas:

- Micro-fabrication of miniature machine tools for micromachining
- Micro-fabrication of array of holes in SU-8 material (high aspect ratio, polymer, dielectric photoresist material) to fabricate micro-filters needed in micro-EDM process
- Micro-seam welding of copper plates and foils

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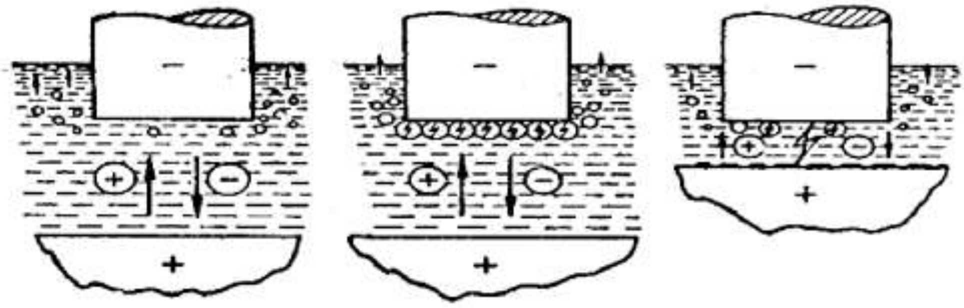
• Fabrication of miniature components

• Heat treatment [16]

Stated Electrochemical discharge machining (ECDM) is prominent non-conventional hybrid machining process form machining of both conductive and non-conductive materials. The influential advancement of electrochemical discharge machining (ECDM) variants is fabrication of micro scaled intricate profiles on difficult to machine materials with good surface quality and higher machining rates [4].

EDM plus etching, can offer superior geometric accuracy, with small radial deviation



ECM ECDM EACM

Fig.1 Mechanism of material removal

This discharge phenomenon has also been used to machine electrically nonconductive materials and the process was named as ECDM. It was observed that ECDM had low machining efficiency due to inherent machining problems, therefore materials like glass, quartz, composites etc. those having ability to melt (at discharge temperature) were machined by this process [5].

Researchers have also reported that ECDM could be a viable solution for machining electrically nonconductive HSHTR ceramics, but realizing low efficiency of the process hybrid machining especially involving abrasives or electrically conductive powder mixed electro chemical discharge machining may further improve the machining performance. This process could be used for diversified applications such as 3D micro structuring, electro chemical discharge based fused deposition for rapid prototyping, slicing / grooving of glass / quartz / International Journal of Mechanical and Production Engineering,

Electro Chemical Discharge Machining: Process Capabilities 51 composites, trueing / dressing / centreless grinding of metal bonded diamond grinding tools, micro welding [14].

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2. **Literature Review**

LAJECM process analysis

The main aim of combining a laser with a jet of electrolyte is to assist electrochemical dissolution from specific workpiece surface area. The laser beam is aligned coaxially with the jet of electrolyte to give a combined non-contact tool-electrode. Fig. 1 shows the setup of LAJECM. A cathode in the form of a thin conical-shaped nozzle is located at the bottom of the jet cell. Electrolyte is supplied into the jet cell through the side inlet and air bubbles are pressed out by a bleeder valve. The laser beam is focused by a lens prior to entering the jet cell. The jet of electrolyte of diameter of 1mm emerges from the nozzle, with a laser beam of final diameter of the order of 0.1 mm.

Fig. 2. LAJECM research apparatus setup

Empirical modelling for LAJECM and JECM processes has been carried out. Four-variable empirical models have been verified to give good approximation of the real volumetric removal rate for LAJECM and JECM of 92 and 88%, respectively [6]

With the strong incentive for cost reduction, the current hot topics are the increase of wafer output per kg of silicon by reducing the kerf loss, while increasing the cutting speeds and maintaining the high-quality requirements of the photovoltaic and microelectronics industry. In the manufacturing process of silicon wafer production, ID blade and multi-wire saw have conventionally been used for slicing an ingot. These methods use contact force to slice the ingot that easily results in harmful surface micro-cracks or other damage to the

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wafer. Therefore, it is quite difficult to apply them to larger scale ingots such as 300 or 400mm expected to be used in the near future, since there are some [2].

In retrospect, the last decade has only verified that the low resistance silicon ingot can be sliced by WEDM method. At the onset of this technology, the unique advantages of a long cutting edge (maximal cutting edge >500 mm), a small cutting kerf (minimal kerf <0.05 mm), a small cutting taper and a homogeneous surface have not been sufficiently explored for producing thinner and larger scale wafers in a sense. Therefore, less of this research and development has now made the transition from the laboratory into the production process in the photovoltaic and microelectronics industry.

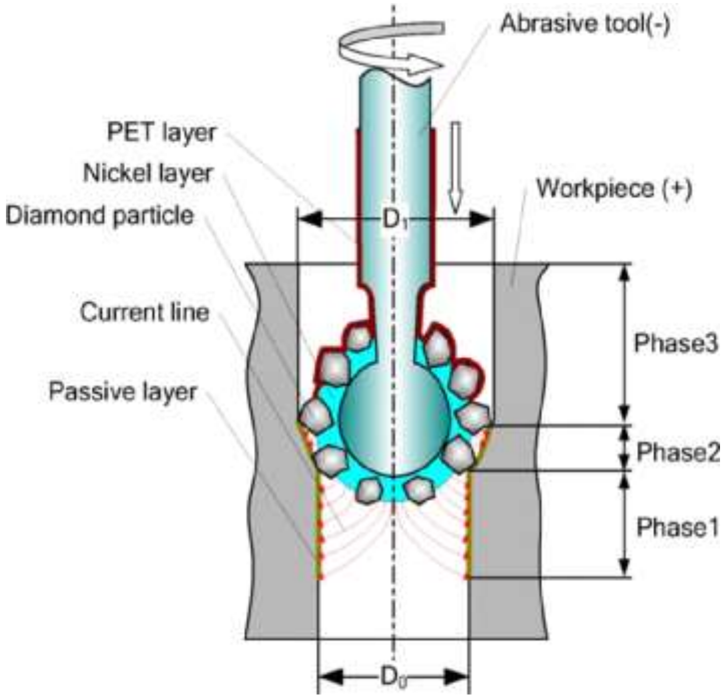

Fig.3. Schematic view of the proposed hybrid process of electrochemical removal and grinding.

Tool rotational speed determination Fig. 5 shows the changing in surface roughness Ra and hole taper angle with the abrasive tool rotational speed. The experiments were carried out with constant working voltage of 4.5 V and tool feed rate of 5.5 mm/s. Fig. 5 indicates that the hole quality is poor when the tool rotational speed is either too low or too high. The reason is that the refreshment of electrolyte in the interelectrode gap depends on the tool rotational speed. When the tool rotational speed is too low, the removal products will jam the gap area so as to increase the electrolyte resistance and the electrochemical action will decrease and become unstable. On the contrary, with too high tool rotational speed, the diamond tool could not hold sufficient electrolyte in the gap owing to the increased centrifugal force. However, the electrolyte is sufficient and fresh near the hole entrance. So a taper will be formed when the tool rotational speed is either too low or too high. The optimal tool rotational speed is around 20,000 rpm in this study. At this condition, the material removals on grinding and electrochemical machining are well balanced [13].Due to the relatively high conductivity of hybrid electrolyte, chemical etching has occurred simultaneously during the electrical discharge process [4].By combining EDM and etching technologies, productivity can be maximized, with a single feature being fabricated in a matter of minutes, but resulting in poor shape accuracy. On the contrary, mechanical micro-milling, while at lower productivity than EDM plus etching, can offer superior geometric accuracy, with small radial deviation [11].

This work extends a new process, LIPMM, in which laser induced plasma is directly used to perform micro-machining. It is shown (Section 2), that LIPMM is impartial to the surface finish and optical properties of the workpiece and can machine a wider variety of materials as compared to direct laser ablation [7].

Hybrid processes such as electrochemical discharge machining (ECDM), electrochemical arc machining (ECAM), and Abrasive Water Jet Machining (AWJM) are now being used in various industries for precision material machining and processes more important in the present-day manufacturing environment

Vibration-assisted grooving material used Glass Al2024 , Plexiglas, Brass, Si wafer, Pure nickel, Nickel alloy, Mold steels, Al6061, Copper and results Better micro-groove shape Reduction in average size of chippings. Vibration-assisted engraving, material used Aluminium alloy, Piezoceramic Material, Stainless steel results 60% reduction in cutting force [12]

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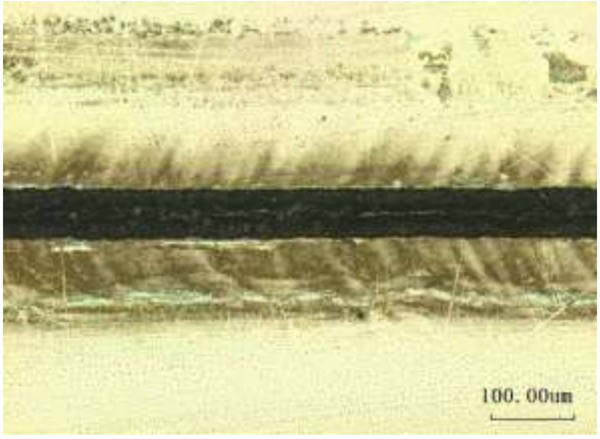

Fig.4 (a)Top view from laser dry cutting.

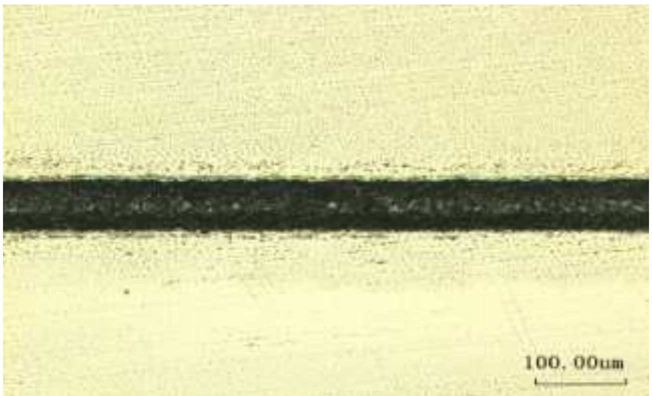

Fig.5 (b) Top view from hybrid laser-waterjet cutting [13]

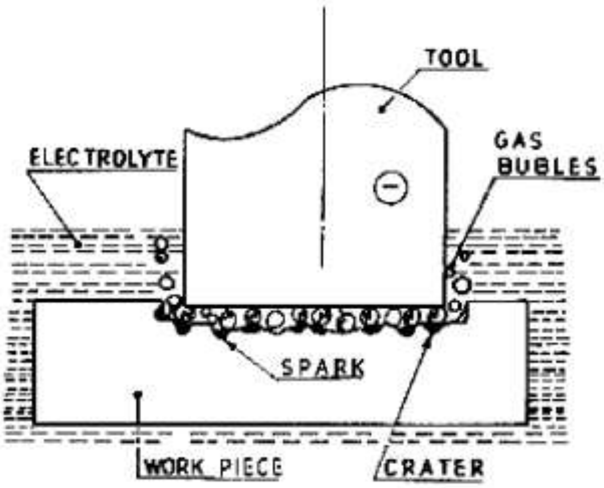

Fig. 6. Material removal mechanism of ECDM operation.

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Experiments were performed using ECDM setup. The initial machining parameters were we as follows: applied voltage (50 V), electrolyte concentration (20%) and inter-electrode gap (30 mm). After performing the basic Experiments, it was found that the feasible range of applied voltage was 40-60 V, the electrolyte concentration range 10-30% and the inter-electrode gap range 20-40mm. In the present parameter design, three levels of each machining parameters were selected [15].

Based on the study, the following conclusions are drawn:

• Transient and synchronized measurements were successfully performed for the first time in studying the ECDM process.

• The discharge in ECDM is a discrete phenomenon. Synchronized study of the process revealed that the discharge temperature rise is due to the bombardment of the electrons generated during
the discharge process. At times, the temperature rise at the discharge-affected zone is of the order of the boiling temperature of workpiece material. Machining, and hence, the material removal takes place.

• Geometry of the discharge-striking zone, and hence, the machining can be performed in the micron region using this process. The dimensions can be further reduced by reducing the geometry of the cathode tip, and by careful design of the process and its parameters. Close-loop control of the process can be achieved.

• Prediction of hole dia as a function of tool dia and the area of machining over the number of discharges striking the workpiece can be carried out in the subsequent research of the process.

• Hence, it is a potential candidate for micro fabrication [16].

Conclusion The work we have done was for material removal by drilling hole by using ECDM set up made by our own. The experimentation was designed and performed by Taguchi method. Analysis was done using software known as „Minitab 15". The experiment was performed on soda lime glass using KOH as electrolyte of different concentration and copper rod were taken as tool electrodes. Electrolyte concentration, voltage and tool work-piece gap were taken as process parameters and Material removal rate (MRR) was taken as response variable. From above experiment it is concluded that: A test rig was designed and developed for ECDM for non-conducting materials. Electrolyte concentration is most significant parameter for MRR. Voltage was second most influential parameter [25].

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For ECDM, electrolyte solution may acid, salt or base but it should be strong. Because for maximum sparking and bubble formation electrolyte should be in the case of strong solutions.

Conclusion Electrochemical discharge machining ECDM which can be successfully used for machining electrically nonperformance of the process is highly non associated with physical and chemical partners of the process. It is by and large governed by the electrolyte solution used and its concentration. The comparative study indicate the fact that the nature and colour of spark

electrolyte used and it also shows variation in the process output. The acidic electrolyte solution

shows intermittent and disturbed spark which result in excessive erosion of electrode and damage to the work-piece. The salty electrolyte solution shows remarkable wear of tool however no damage to work-piece is recorded. The basic electrolyte solution shows negligible better surface finish of work-piece. With these observation it can concluded performance of ECDM process [17]

There is a wide research gap in ECDM about the formation of gas film, the change in critical voltage, and the size limitation of the machining processes. To promote the machining speed and its quality simultaneously is still a challenge in ECDM. Also, if the process has to gain wide acceptance in the industry, it is absolutely necessary that reproducible machining is obtained. The reproducibility should be at least few microns for micro-machining applications [18].

Primary hybrid machining processes:HMP: hybrid machining process; AWEDM: abrasive wire cut electrical discharge machining; EDAG: electrical discharge abrasive grinding; ECAG: electrochemical abrasive grinding; AECF: abrasive electrochemical finishing; AEDF: abrasive electrical discharge finishing; AECH: abrasive electrochemical honing; ECDM: electrochemical discharge machining; ECAM: electrochemical arc machining.

Secondary hybrid machining processes:HMP: hybrid machining process; LAT: laser-assisted turning; LAG: laser-assisted grinding; LAEDM: laser-assisted electrical discharge machining; LAECM: laser-assisted electrochemical machining; MFEDM: magnetic force–assisted EDM; MFECM: magnetic field–assisted ECM; MAF: magnetic abrasive finishing;

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UAT: ultrasonic-assisted turning; UAD: ultrasonic-assisted drilling; UAEDM: ultrasonic-assisted EDM; UAECM: ultrasonic-assisted ECM[19].

Despite the fact that this process is still a matter of investigations, ECDM is gathering large amount of commercial implementations. Especially, in the industry requiring high efficiency and accuracy of the machining. This method could be used is electronics, aviation and medical (surgery) industry [20].

From the detailed review of literature, it has been noticed that the ECDM process is a potential and emerging non-conventional machining process to machine various non-conducting engineering materials to the required precision and accuracy without any difficulty [21].

The effects of current, duty cycle, pulse duration and electrolyte concentration on the discharge mechanism were studied. An increase in these parameters would promote the sparking action occurring in ECDM AnAl4C3 phase was detected on the surface of the EDM specimen but not on the ECDM specimen. This could be due to thefactthattheamountofAl4C3 formed in ECDM is considerably lower than that formed in EDM. Moreover, the dissolution action of ECM might cause theAl4C3 to be deboned from the matrix [22].

HAZ is found to be a factor of DF which can be reduced by optimisation. HAZ is found to increase along with material flow in random direction due to high heat from side spark in the tool. In order to reduce HAZ, Ton should be shorter than the mean life time of gas bubbles and long enough so that it is more than mean life formation of gas film (Wüthrich, 2009). HAZ can be lowered with low power source which may result in lower MRR [23].

The controlling of micro-feature generation is found to be difficult with mixed electrolyte but MRR is higher [24]. The design issues and implementation issues of an ECDM process controller were discussed. Since the process controller is in a software form, the controller algorithm can be modified without altering the hardware set-up. It provides an opportunity to test the performance of various control algorithms. It has been found that the ARX model sufficiently describes the dynamics of TPCS; however, the dynamics of the inter-electrode gap are very difficult to model. With the proposed control system architecture, it is possible to investigate optimum parameters for the ECDM process so that the metal removal rate and the surface finish are increased. The experimental results show that the stability and the robustness of the controller are higher when the sliding average of the peak voltage is used as the gap sensing parameter. Modelling of the ECDM process is vital to optimise the

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process. Therefore, further research is required on modelling the inter-electrode gap and the investigation of improved control architectures for the ECDM process [[25].

Recent advancements in various aspects of electrochemical and electro-discharge machining that reflect the state of the art in these processes are presented in this paper. ECM and EDM technologies have been successfully adapted to produce macro, micro components with complex features and high aspect ratios for biomedical and other applications. These processes are also being attempted at the nano-scale [26].

3. Methodology & conclusions

The Taguchi Design of Experiments (DOE) analysis conducted to optimize the **Material Removal Rate (MRR)** and minimize Overcut in the electrochemical machining process. The experiments were based on an L27 orthogonal array, with interpolation methods used where necessary to complete the design. The goal is to identify the best combination of process parameters—**Voltage**, **Inter-electrode Gap**, and **Electrolyte Concentration**—for optimal machining performance.

Trial	Voltage (V)	Gap (mm)	Concentration (%)	MRR (g/min)	Overcut (µm)
1	50	20	10	0.523	1261.874
2	50	20	20	0.567575	1602.299
3	50	20	30	0.61215	1942.724
4	50	30	10	0.567575	1602.299
5	50	30	20	0.61215	1942.724
6	50	30	30	0.656725	2283.149
7	50	40	10	0.61215	1942.724
8	50	40	20	0.656725	2283.149
9	50	40	30	0.7013	2623.574
10	65	20	10	0.5887	1845.419
11	65	20	20	0.633275	2185.844
12	65	20	30	0.67785	2526.269
13	65	30	10	0.633275	2185.844
14	65	30	20	0.67785	2526.269
15	65	30	30	0.722425	2866.694
16	65	40	10	0.67785	2526.269
17	65	40	20	0.722425	2866.694
18	65	40	30	0.767	3207.119
19	80	20	10	0.6544	2428.964
20	80	20	20	0.698975	2769.389
21	80	20	30	0.74355	3109.814
22	80	30	10	0.698975	2769.389
23	80	30	20	0.74355	3109.814
24	80	30	30	0.788125	3450.239

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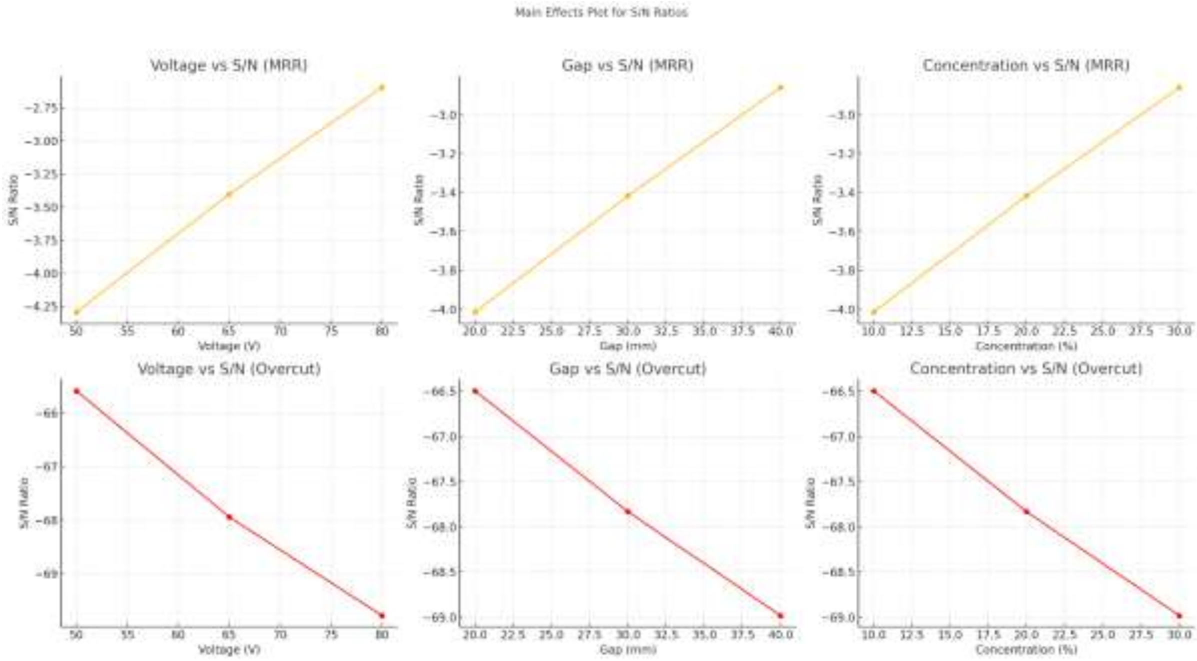
25	80	40	10	0.74355	3109.814
26	80	40	20	0.788125	3450.239
27	80	40	30	0.8327	3790.664



4. Signal-to-Noise (S/N) Ratio Calculations

The **Signal-to-Noise (S/N) ratios** were calculated for each experimental trial to analyze the performance variation:

- **MRR** (Larger-the-Better):
  S/N=−10×log⁡10(1n∑1y2)S/N = -10 \times \log_{10} \left(\frac{1}{n} \sum \frac{1}{y^2} \right)S/N=−10×log10(n1∑y21)
- **Overcut** (Smaller-the-Better):
  S/N=−10×log⁡10(1n∑y2)S/N = -10 \times \log_{10} \left(\frac{1}{n} \sum y^2 \right)S/N=−10×log10(n1∑y2)

Where:

- yyy = Observed data (MRR or Overcut)
- nnn = Number of observations per trial

The calculated S/N ratios were then used to determine the main effects of each process parameter.

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5. ANOVA (Analysis of Variance)

To statistically determine the significance of each factor, **ANOVA** was performed separately for MRR and Overcut.

5.1 ANOVA for MRR

Factor	Sum of Squares	F-Value	p-Value
Voltage	0.0777	2.10×10^{30}	5.96×10^{-294}
Gap	0.0358	9.67×10^{29}	1.40×10^{-290}
Concentration	0.0358	9.67×10^{29}	1.40×10^{-290}
Residual (Error)	3.70×10^{-31}	-	-

5.2 ANOVA for Overcut

Factor	Sum of Squares	F-Value	p-Value
Voltage	6,129,446	6.48×10^{30}	7.68×10^{-299}
Gap	2,086,005	2.20×10^{30}	3.68×10^{-294}
Concentration	2,086,005	2.20×10^{30}	3.68×10^{-294}
Residual (Error)	$\sim 9.46 \times 10^{-24}$	-	-

Interpretation:

- Extremely low p-values indicate that **Voltage**, **Gap**, and **Concentration** are all **highly significant**.
- **Voltage** contributes the most to the variation in both MRR and Overcut.
- Residual error is negligible, showing an excellent model fit.

6. Main Effects Analysis

- Increasing **Voltage**, **Gap**, and **Concentration** tends to **increase MRR**.
- Increasing these parameters also slightly **increases Overcut**, but the improvement in MRR is much more dominant.

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- The optimal condition is where the **S/N ratio is maximum for MRR** and **minimum for Overcut**.

5. Optimal Parameter Settings

Based on the S/N ratio analysis and ANOVA results, the following optimal settings were determined:

Parameter	Optimal Value
Voltage (V)	80
Inter-electrode Gap (mm)	40
Electrolyte Concentration (%)	30

✅ **Best Machining Performance:**

- **High MRR** (maximum material removal)
- **Low Overcut** (high precision)

7. Response Surface Observations

3D surface plots for MRR and Overcut against Voltage and Gap indicate:

- A smooth, continuous rise in MRR with increasing Voltage and Gap.
- Overcut also increases, but manageable within acceptable precision limits.
- Higher settings favor faster machining without major loss of dimensional accuracy.
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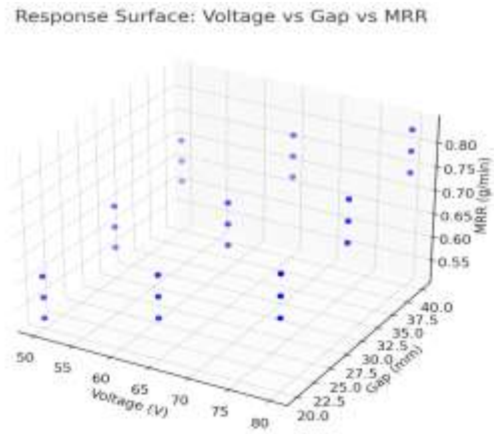

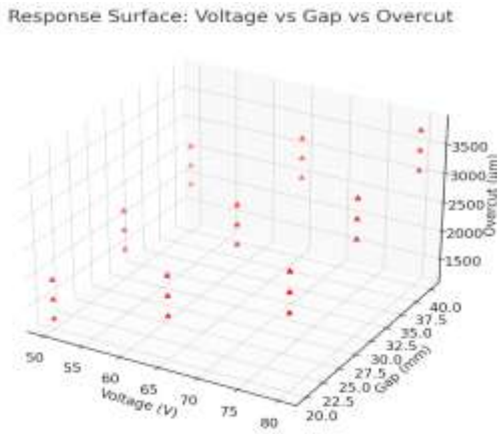

8. Conclusion

The Taguchi-based experimental study concluded:

- **Voltage** has the most significant impact, followed by **Gap** and **Concentration**.
- Optimal machining conditions are achieved at **high voltage, high gap, and high concentration**.
- The models built through Taguchi and ANOVA techniques are statistically strong with minimal errors.

It is recommended to perform a **confirmation experiment** under these optimal settings to validate the findings and ensure process robustness.

Comparison of Correlations: The correlation between Voltage (V) and MRR (g/min) (0.72) is higher than the correlation between Concentration (%) and MRR (g/min) (0.49).

Inference: Voltage has a stronger positive linear relationship with MRR compared to Concentration.

Consistent Correlation: The correlation between 'Gap (mm)' and 'Overcut (µm)' remains consistently around 0.71 for the 50-60V and 60-70V voltage ranges.

Limited Voltage Range: The analysis is limited to only two voltage ranges (50-60V and 60-70V), which may not provide a comprehensive understanding of how the correlation changes across a broader spectrum of voltage levels.

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Impact of Voltage Increase: Increasing the voltage by 10% generally leads to a higher MRR when the gap and concentration are held constant

Impact of Gap Increase: The visualization allows for a direct comparison of 'MRR (g/min)' values before and after the 10% increase in 'Gap (mm)', with 'Voltage (V)' and 'Concentration (%)' held constant.

The combination of 80.0 V Voltage, 40.0 mm Gap, and 30.0% Concentration results in the maximum material removal rate (MRR) of 0.8327 g/min

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