MACHINABILITY STUDY OF SPARK ASSISTED CHEMICAL ENGRAVING (SACE): A STATE OF ART

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Abstract
Spark assisted chemical engraving (SACE) is a triumph process for processing the non-conductive materials such as glass, ceramics, composites, quartz, and so on regardless of their physical properties. It shows different criticalness in the field of microelectromechanical systems (MEMS) and lab-on-chips for manufacturing items with the miniaturized scale on a large scale. Due to the increasing demand for micro-components such as microsensors, micro-batteries, micro-needles, etc in aerospace, nuclear, and medical industries, there has been an escalation in the product miniaturizations. The material removal phenomena in SACE is a consolidated impact of electrochemical machining (ECM) and electric discharge machining (EDM) together. This article discusses the fundamental principles, recent studies, and influential parameter’s effect on gas film stability. Moreover, the performance enhancement of the SACE process and the influence of varying discrete process parameters includes applied voltage, electrolyte concentration, tool feed rate, tool shape is discussed. Result revealed that any change in the applied voltage and electrolyte concentration results in the variable spark intensity over the work material. Tool shape significantly affects the formation of the stabilized gas film at its vicinity and its feed rate controls the effective machining gap for electrolyte availability. The present study on SACE reveals that machining with an optimum range of input parameters is crucial for its effectiveness and repeatability. The study highlights the conceivable future regions to improve the machining performance of the SACE process.

Keywords: SACE, micro-holes, material removal rate (MRR), gas film, spark, spherical tool.

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I. Introduction

With a fast increment in the demand of micro-products in the advanced industries like aerospace, bio-medical, nuclear, optics, electronics and communication industries, etc., there has been progressive development in the micro-machining processes. It starts the micro-fabrication of the pioneer engineering materials that include advanced ceramics, superalloys, etc. Moreover, the use of non-conductive materials such as quartz, glass, and ceramics, etc. has also been increasing drastically over the past years, due to some favorable characteristics or peculiar properties. These materials may refer to as “difficult to machine” materials as they are hard and brittle. Despite having several advance technologies, still many challenges are being faced by scientists and researcher to machine these materials such as laser beam machining (high investment, undesirable heat-affected zone (HAZ)), abrasive water jet machining (hazardous, high investment, high maintenance), ultrasonic machining (high cost, tool wear, tool bending), etc. Thus, there is a need for a more sophisticated and advanced machining process, having the potential of machining these engineering materials by confronting up the difficulties faced in other machining processes. Spark assisted chemical engraving (SACE) process has the tremendous potential of machining these “difficult to machine” materials by combining the material removal mechanism of both the electrochemical machining (ECM) and electric discharge machining (EDM) simultaneously. The removal occurs due to the thermal melting of the work material followed by chemical dissolution. It has the following achievements in machining (i) Discrete new materials or hard and brittle materials, (ii) Dimensional accuracy and high surface finish, (iii) higher material removal rate.

SACE exhibits numerous applications in the field of micro-manufacturing. Materials, which are strenuous to process such as glass, quartz, ceramics like aluminum oxide, silicon nitride, etc, can be easily machined by this process. It has one of the distinct advantages of machining the materials regardless of their hardness via thermal energy.

There are more fundamental advantages of SACE process as given below:

- The machining method is independent of the material's chemical and physical properties.
- No external force is required to remove the material.
- Reduced occurrence of the heat-affected zone (HAZ).
- No requirement for skilled labor.

The SACE process has an extensive variety of applications in the micro-machining as follows: (i) glass micro-texturing for micro-fluidic applications such as micro-bioreactors and micro-mirrors [1]. (ii) Miniaturization of components such as micro-scale fuel cells, miniature gears, and micro-scale pumps [2]. (iii) micro-fabrication of the glass material for MEMS and other industries such as microbiological laboratories, astronomy, etc. [3], (iv) Fabrication of micro-holes on SU-8 material in array form for MEMS [2] and (v) Biomedical equipment's i.e., biosensors [4]. Chang et al. [5] fabricated micro-holes in glass by utilizing a 200 μm diameter cylindrical tool electrode at two applied voltages (40V and 45 V). Zheng et al. [6] used a layer-by-layer technique to fabricate 3D microstructures on the glass with applied voltage in pulsed form as shown in Figure 1.

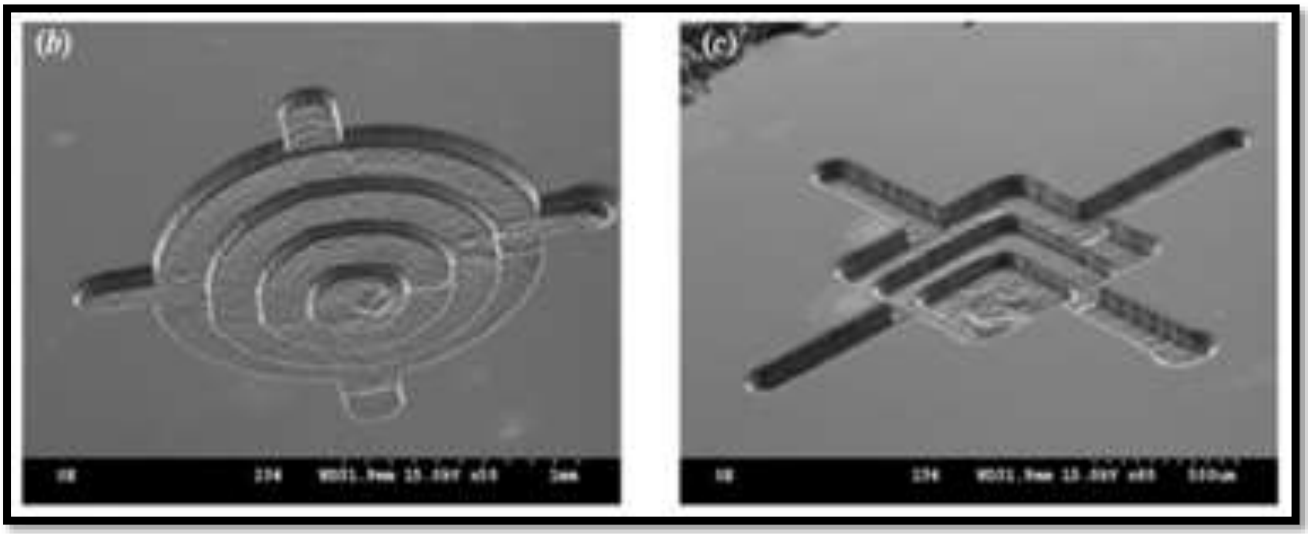

Figure 1: Micro-structure fabricated with SACE [6]

1.1.Historical Developments in SACE process

The SACE was first demonstrated by Kurafuji and Suda in 1968 [7], in which they successfully performed drilling on the glass materials. The process involved the machining characteristics of both the ECM and EDM. They evaluated the effect of electrolyte composition on the removal rate of the material. Thereafter, the developments in the SACE process has been growing with keeping in mind the objective of maximizing its machining performance. It is popularly known by the electrochemical discharge machining (ECDM) process [8-12]. The summary of SACE developments is highlighted in Table 1.

2. SACE WORKING PRINCIPLE

The SACE process comprises a tool electrode (or cathode) and auxiliary electrode (or anode), both immersed in an alkaline electrolyte (NaOH, KOH, etc.) and separated by a distance of few centimeters (known as IEG) as shown in Figure 2.

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Table 1 Historical development in SACE process

YEAR	DEVELOPMENT	REPORTED BY
1968	The first-time drilling in SACE was performed on the glass.	[7]
1972	The first electrochemical grinding apparatus was made.	[8]
1975	Developed an improved electrode structure for the electrochemical discharge machining of a metallic work-piece.	[9]
1985	Studied the discharge mechanism in electro-chemical arc machining.	[10]
1996	First time machining of partially conductive piezo-electric ceramic and carbon fiber epoxy composite.	[11]
1999	The 3D microstructure was fabricated on glass using SACE.	[12]
2004	Build a Fuzzy logic control for SACE.	[13]
2005	Surfactants mixed electrolyte.	[14]
2007	Additives mixed electrolyte.	[15]
2009	Ultrasonic vibrated electrolyte.	[16]
2010	Magnetic field-assisted SACE.	[17]
2011	Use of Spherical tool electrode.	[18]
2012	Machining of E-glass fiber epoxy composite.	[19]
2013	Rotary tool electrode.	[20]
2015	Developed a mathematical model for predicting overcut in SACE.	[21]
2016	Micro-machining on Nickel-based superalloy.	[22]
2017	Electrochemical discharge drilling on beryllium copper alloys.	[23]
2018	Textured tools in SACE micro-channeling.	[24]
	Developed a pressurized feeding system for an effective machining gap.	[25]
2019	Numerical and experimental analysis of the SACE process during micro-channeling	[26]
2020	Numerical analysis of SACE process using electromagnetic filed	[27]

A pulsed or continuous direct current (DC) power is applied between anode and cathode to complete the circuit. It triggers the electrolysis process which starts the formation of tiny hydrogen and oxygen gas bubbles at the electrodes. With further increase in voltage (> critical voltage), the generation rate of tiny bubbles (oxygen and hydrogen) also increases due to the increase in electrochemical reactions and electrolyte ohmic heating. These tiny bubbles start coalescence with each other. As the generation rate of hydrogen bubbles becomes higher than the generation rate of the bubbles floating on the electrolyte, then bubbles start coalescence physically to form a big size bubble (or hydrogen gas film) which isolates the tool electrode [28,29]. Figure 3(a) illustrates the mechanism of gas film formation while Figure 3 (b) shows the stepwise spark generation mechanism in the SACE process.

The hydrogen gas film behaves as an insulator around the tool (also known as tool blanketing) which abruptly terminates the flow of electric current and generates an immense electric field over the dielectric film produced between cathode tool and electrolyte, which further results into spark (or arc discharge). The removal of the work material in SACE occurs primarily due to the melting and evaporation of the work-piece [29-34] and partially due to chemical action [35-37].

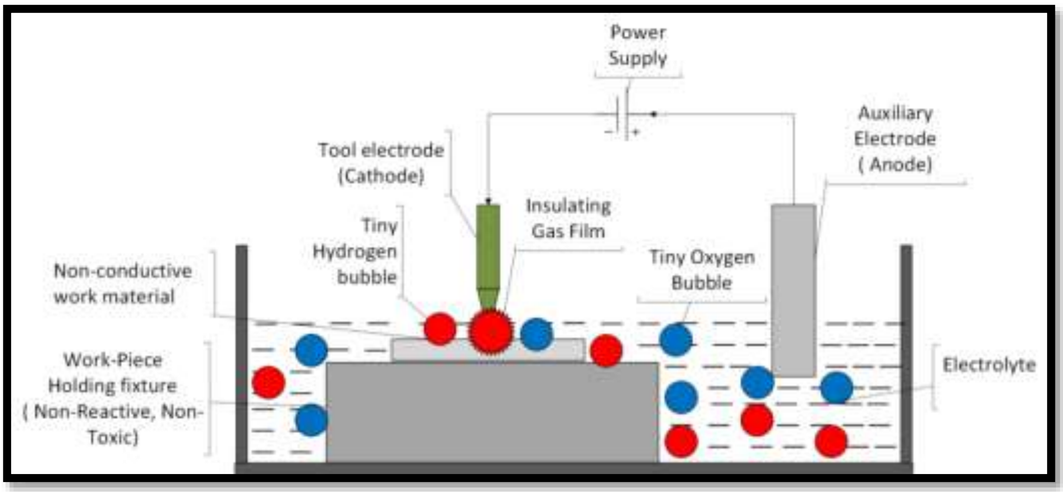

Figure 2: Schematic diagram of SACE [30].

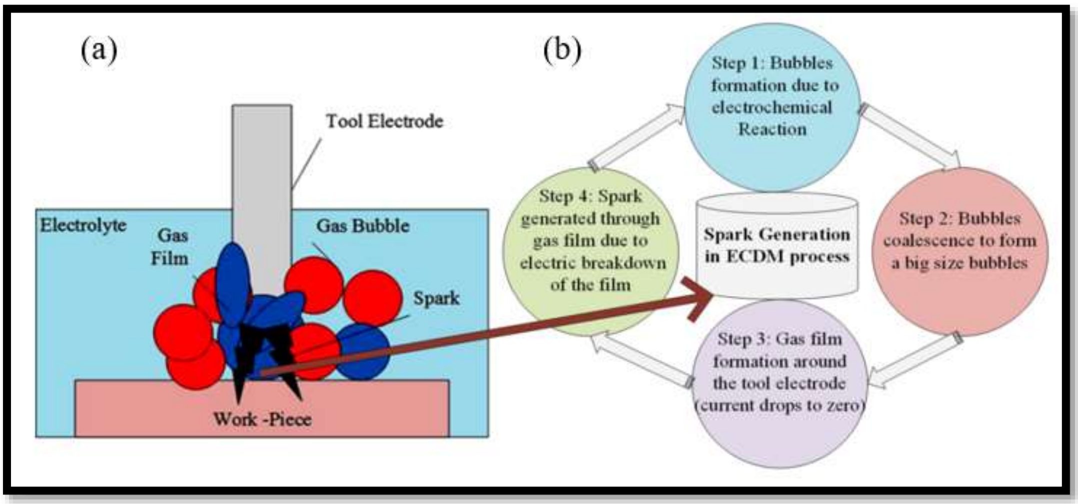

Figure 3: (a) Gas film formation around tool electrode, 3(b) Step-wise spark generation [30].

3. LITERATURE STUDY

Spark generation mechanism in SACE was first demonstrated by Basak and Ghosh [38, 39] in which they emphasized that critical value of voltage and current are required for initiating the spark and machining process. They further stated that the spark mechanism is similar to an On/Off action of a switch. Wuthrich et al. [40] described that immense current intensities are produced at the sharp edges of the tool electrode, requiring tool electrode (cathode) to be made of thinner section as compared to tool anode (auxiliary). Jain et al. [41] detailed a valve theory that considered each gas bubble as a valve that produces spark once its electric breakdown takes place.

El-Haddad et al. [42] predicted the current values for stabilized gas film formation by taking into account the gas film dynamics. Further, Fascio et al. [43] divided the typical current-voltage characteristics of SACE into five regions as shown in Figure 4 and Table 2. Vogt [44] explained the gas film mechanism based upon wettability and suggested that change in tool electrode wettability results in variable gas film thickness. It was concluded that the tool electrode material and electrolyte concentration are the reasons responsible for the change in wettability. Kulkarni et al. [45] experimentally investigated the spark mechanism in SACE during the machining of different work materials. The experiments were carried out at 5 wt% HCl and 155 V. They found that the magnitudes of the current values were different despite the similarity in their variations. Behroozfara et al. [46] investigated the plasma channel's characteristics and material removal in the SACE process during the microfabrication of the glass. The finite element modeling (FEM) based thermo-physical model was successfully developed for determining the material removal in the SACE process. They obtained a plasma diameter of 260 μm. Many researchers [47-50] reported that the material removal mechanism majorly depends upon the gas film that builds at the tool vicinity. Thus, gas film stability needs to be controlled for obtaining high-quality machining surface. Many parameters control the gas film stability like electrolyte concentration, tool electrode shape, tool wettability, electrolyte viscosity, etc [51].

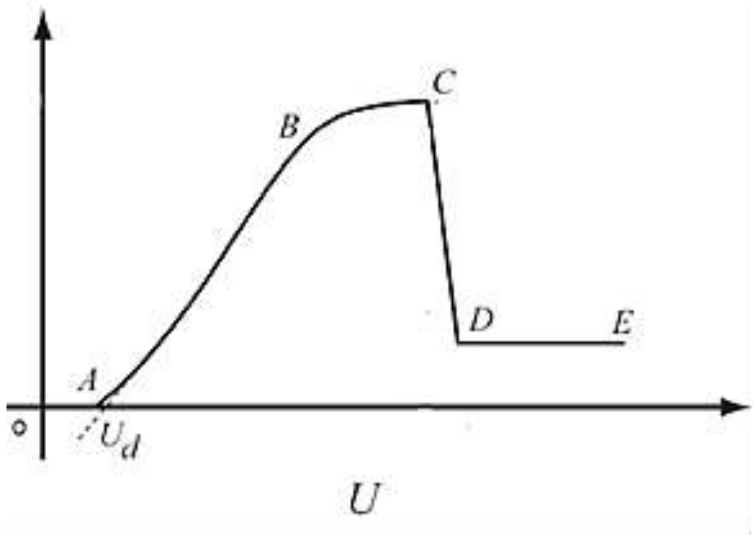

Figure 4: Typical current-voltage characteristics in the SACE process [40].

Table 2 Different regions of Current-voltage characteristics in the SACE process.

POINTS	REGION	VOLTAGE VALUE	PROCESS	CURRENT
O-A	Thermodynamic region	$0<U<U_d$	No Electrolysis	No Current
A-B	Ohmic region	$U_d<U<U_{lim}$	Electrolysis takes place	Current varies linearly
B-C	Limiting the current region	$U_{lim}<U<U_{crit}$	Coalescence of bubbles start	Reaches Limiting Value, I_{crit}
C-D	Transition region	$U_{crit}<U<1.2U_{crit}$	Gas film formation around tool electrode	Current decreases rapidly
D-E	Arc region	$U>1.2U_{crit}$	Arc discharge takes place	Current seizes

where I is mean current, I^{crit} is critical current density, U is applied voltage, U^{lim} is limiting voltage, U^{crit} is critical voltage and U_d is water decomposition voltage.

Pulse voltage is one such method to control the gas film stability in which sparks are produced in a periodical manner. It helps in maintaining the smaller gas film thickness which further reduces the quality variation on the machined surface [51]. Sathisha et al. [52] carried out a study on material removal rate (MRR) and tool wear rate (TWR) by varying the input parameters like machining gap, electrolyte concentration, and applied voltage. Grey relational analysis (GRA) based multi-response optimization was performed to identify the optimum parameters. Results revealed that the machining gap was the most dominant factor controlling the MRR and TWR simultaneously.

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Bhuyan et al. [53] have signified that the machining performance depends upon the selection and range of input parameters. Experiments were also conducted to investigates the effects of voltage, pulse on-time (T_{on}), and electrolyte concentration on the removal rate and surface roughness (Ra). An increase in both the pulse on-time and applied voltage leads to an increase in removal rate and roughness. Wuthrich et al. [54] investigated that the removal rate of material and wear rate of the tool increases with the increase in electrolyte temperature and applied voltage.

McGeough et al. [55-56] concluded that applied voltage and feed rates are one of the most influential parameters in determining MRR as its rate increases at higher voltage and feed rate. Similar results were given by Harugude [57] as shown in Figure 5. Cao et al. [58] reported that a change in applied voltage toward the higher side increases the MRR along with the depth of machining (up to 55 μm). An increase in the mixed concentration of KOH and NaOH enhances the electrical conductivity which improves the chemical etching [59]. Similar findings were observed during the machining of silicon nitride with increased NaOH concentration [60]. Bhattacharyya et al. [61] explored different tool shapes during machining with SACE. They observed that tool electrode with a pointed tip and tapered sidewall are the most adequate tools for fabricating circular holes.

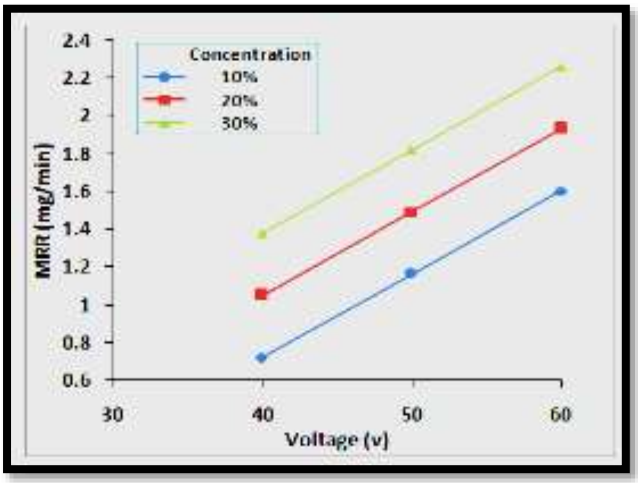

Figure: 5 MMR at different applied voltages [57].

Goud et al. [63] evaluated an optimum parametric combination of input process parameters while machining micro-channels on quartz glass. Material removal rate (MRR) and width over the cut (WOC) were optimized by utilizing the multi-response technique i.e., grey relational analysis. Feed rate was observed as the most dominating factor for combined responses. Jawalkar et al. [64] experimented to analyze the influential parameter's effect on machining characteristics along with their contributions in SACE machining. Applied voltage computed as the most influential parameter for determining the removal rate of the glass. Rajput et al. [65] compared the machining performance of the cylindrical and pointed tool electrode in terms of MRR. It was found that the pointed tool electrode results in more removal of the work material due to enhanced flow of electrolyte between the tools and work material. Singh et al. [25] build up a pressurized feeding system for maintaining effective control of the machining gap during micro-drilling operations using SACE. Stainless steel coated with 30 μm SiC abrasives was used as a tool electrode. They computed that the pressurized feeding system provides effective control on the machining gap which further results in precise machining in SACE.

Yang et al. [62] observed a decrease in hole entrance diameter using a spherical tool electrode due to the reduction in the contact area across the tool sidewall and work material. It enhances the electrolyte flow to the electrode end. This results in a quick formation of the gas film and produces efficient micro-holes as shown in Figure 6. Rajput et al. [30] studied the parameter's effect on

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different responses and highlighted the future areas for enhancing the SACE machining performance. Apart from experimental studies, numerous analytical studies were also reported regarding analyzing the performance of the SACE. Various thermal model based upon FEM was described to analyze the removal rate of the SACE process.

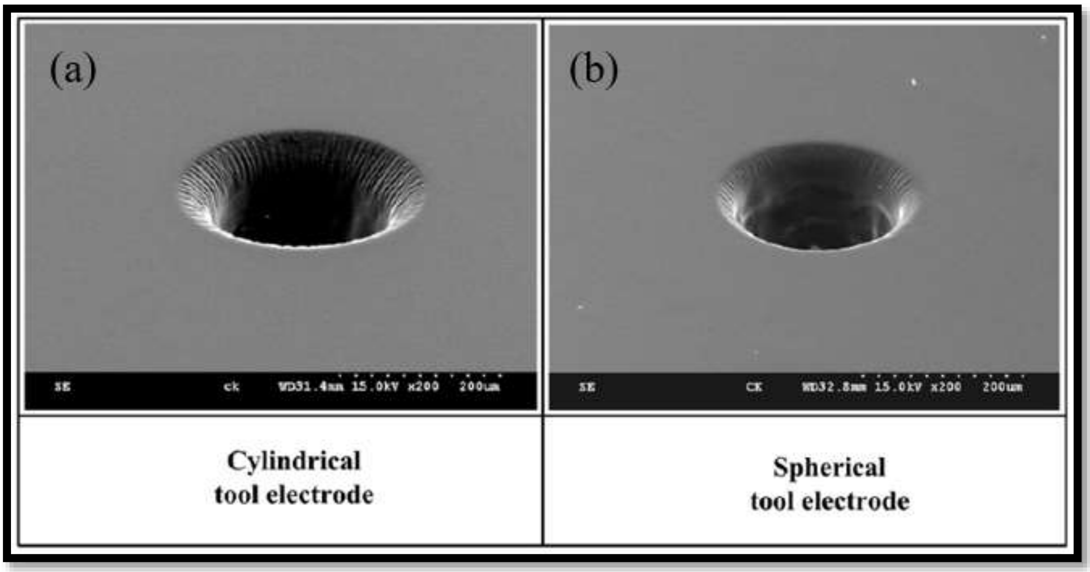

Figure 6: Micro-holes machined using different tool shapes, (a) increased diameter of hole entrance with the cylindrical tool and (b) reduces the diameter of hole entrance with spherical tool [62].

Bhondwe et al. [66] successfully build a transient thermal model for analyzing the removal rate of work material by utilizing the temperature distribution plots. Gaussian heat distribution was utilized within the spark region. A good agreement was observed between the experimental and simulated results. Wei et al. [67] also simulated the SACE machining process for the discharge regime and computed that a total of 29.1 % energy is transferred to the work material. Goud et al. [68, 69] build a 3D thermal model based on FEM for estimating material removal. They found that the experimental results are in fair agreement with the simulated results. They also revealed that MRR improves with the rise in electrolyte concentration. Recent analytical studies on SACE demonstrated the application of electromagnetic fields and electric currents for analyzing the performance of the SACE.

4. RESEARCH FINDINGS ON PERFORMANCE ENHANCEMENT IN SACE

Machining performance of the SACE process is majorly depending upon material removal rate, quality of machined surface, and tolerances. In SACE, input process parameters and their selections play a very crucial role in determining its performance. Various researchers have put forward their explanations regarding the process parameter’s effect on enhancing the material removal rate. The cause-and-effect diagram of almost all influential input parameters in SACE is shown in Figure 7. This section discusses the critical research findings of the previously reported work during SACE machining.

4.1. Effect of the applied voltage

Material removal rate (MRR) of any non-conductive material improves with the rise in applied voltage, as the generation rate of hydrogen bubbles increases which further enhances the intensity of spark frequency. It directly affects the machining efficiency of the SACE process because higher voltage tends to create thermal cracks [70], while lower voltage is required or maintained to ignite thermo-chemical reactions [71].

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Various authors reported that applied voltage serves a dominant role in controlling the removal rate of the material [66-72]. Lizo et al. [72] investigated the removal rate of the material concerning increasing voltage at three different voltage levels (35V, 40V, 45V) during the micro-channeling process. It was found that an increase of 1.03 mg in MRR occurs with the increment in the voltage from 35 V to 45 V due to the increased rate of sparking. As a result, higher thermal energy was transferee dot the work material and thus giving higher MRR. But too much higher voltage may also result in the thermal cracks at the micro-hole edges. Similar results were given by Cao et al as seen in Figure 8 [58].

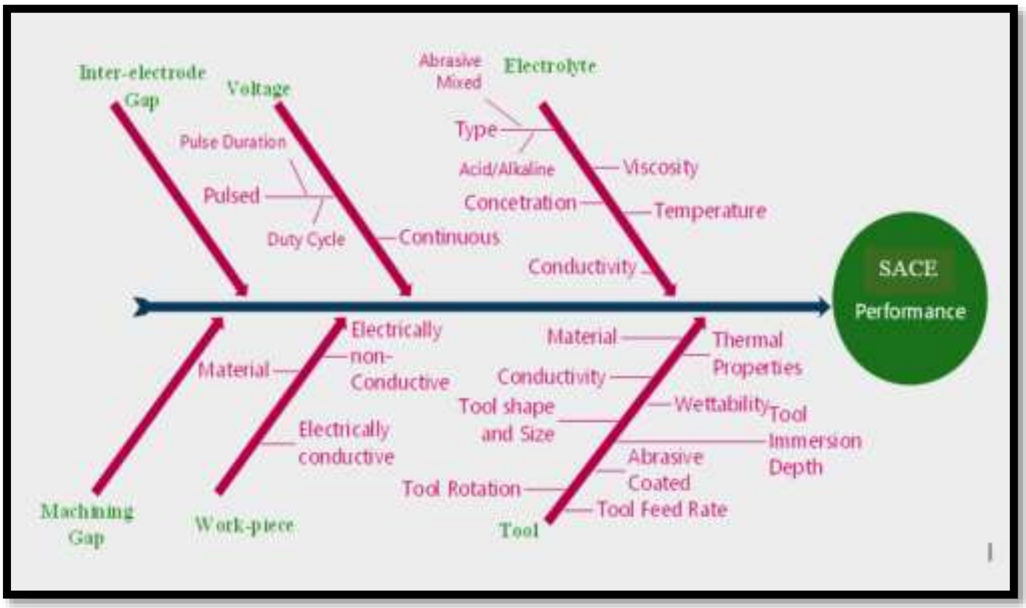

Figure: 7 Cause and Effect diagram of effective process parameters in SACE.

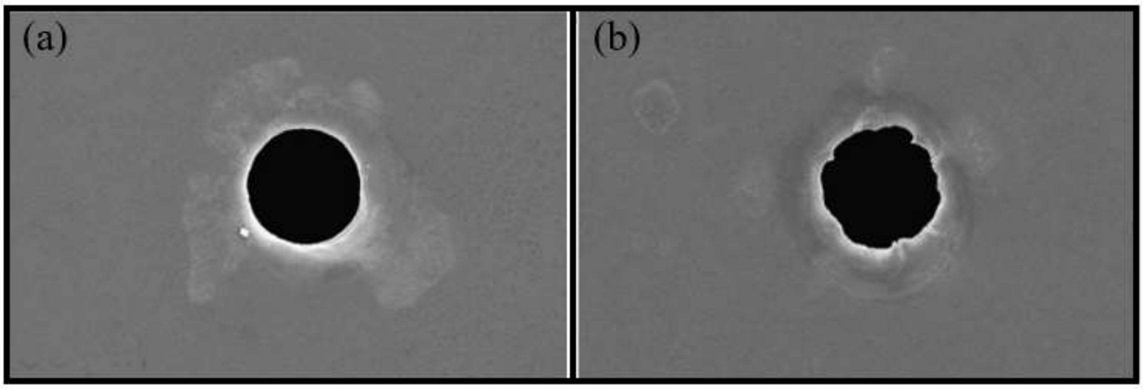

Figure 8: Hole exit (a) No thermal cracks when drilled at 30 V (b) Thermal Cracks when drilled at 35V. KOH 30wt%, Ø 30 µm, 1ms/1ms pulse on/off-time ratio and 300 rpm rotational speed [54].

Various studies reported that the use of pulse voltage over continuous voltage for preferable MRR alongside good finish of the machined surface. In pulse voltage, the sparks occur periodically or only during the pulse on time (T_{on}). It prevents excessive thermal damage on the work material's surface. An increase in pulse on time improves the removal rate due to a high number of sparks but high heat-affected zone (HAZ), high thermal damage and overcut can occur if prolonged Pulse on time (T_{on}) exists [73]. This high exposure of heat due to the long pulse on time can be minimized by activating the pulse-off time (T_{off}). Pulse off time (T_{off}) enhances the cooling of the tool electrode [74-75]. Figure 9 shows the summarized report on applied voltage effect on SACE performance.

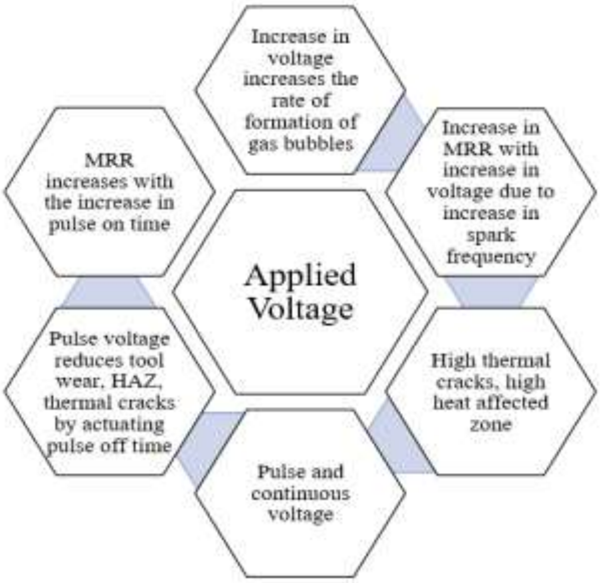

Figure: 9 Summarized report on applied voltage effect on SACE performance.

4.2. Effect of electrolyte concentration

The increase in electrolyte concentration results in the increase in the number of individual ions inside the electrolyte and hence the electrolyte's conductivity is enhanced. An increase in electrolyte conductivity produces a higher rate of hydrogen bubbles. Thus, a rapid gas film is formed and as a result, high intensity of sparks over the work material is produced. Thus, the removal rate of work material improves with the increase in electrolyte concentration [58, 70-72]. Figure 5 demonstrates the increase in MRR with an increase in electrolyte concentrations. A dense and thin gas film can be achieved at a lower voltage and higher electrolyte concentration, thus lowering transition voltage [76]. Malik et al [77] observed an improvement in MRR with the rise in electrolyte concentration from 50g/l to 200g/l during the machining e-glass fiber epoxy composite with NaOH electrolyte as seen in Figure 10.

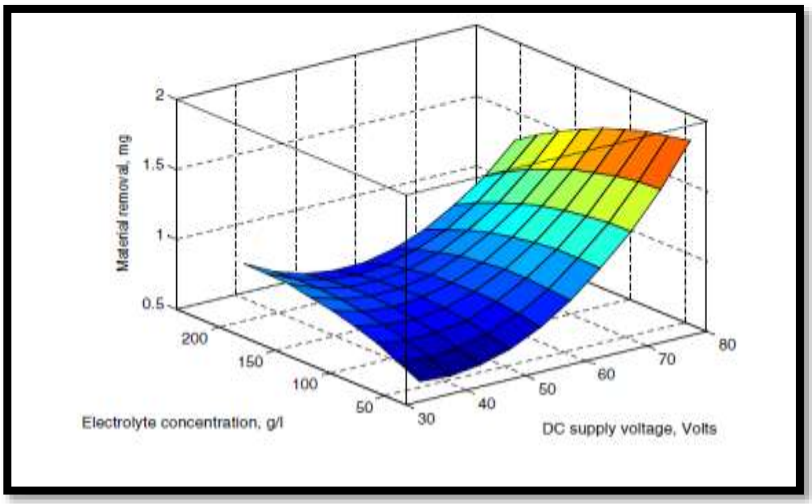

Figure: 10 MRR at different electrolyte concentrations [77].

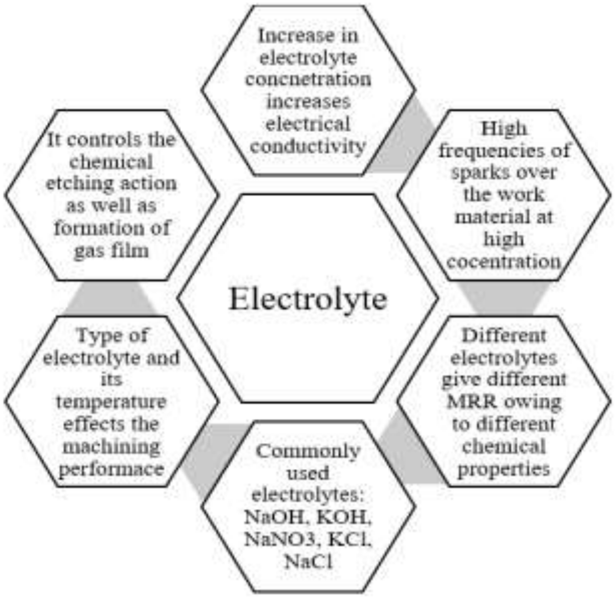

Figure: 11 Summarized report on electrolyte effect on SACE performance.

Rajput et al. [78] evaluated the influence of electrolyte and its concentration on MRR during micro-hole operation with SACE. NaOH, KOH, and NaCl were selected as the different electrolytes. They found that NaOH produces the highest MRR amongst all the electrolytes and removal rate improves with the increase in electrolyte concentration. It was explained that alkaline electrolytes give higher material removal compared to NaCl due to the presence of OH ions. OH^- ions are necessary for etching action and an increase in concentration enhances the etching action of the electrolyte. Figure 11 shows the summarized report on the electrolyte effect on SACE performance.

4.3. Effect of electrolytes mixed with abrasives and surfactants

The surface quality of the machined surface can be improved by mixing abrasive particles into the electrolyte. It results in the enhancement of the abrasive action that results in the refinement of the micro-cracks as reported by various researchers [79, 80]. Yang et al. [81] mentioned that the gas film stability is deteriorated by mixing abrasives sue to the fact that their presence continuously disrupts the machining gap. As a result, the critical voltage value rises. An increase in abrasive concentration enhances the MRR due to the improvement in abrasion action and critical voltage. Mohammad et al. [82] added surfactants to the electrolyte that alters the electrolyte's physicochemical properties, thereby reducing the gas film thickness. Sodium dodecyl sulfate (SDS) and Cetyltri methyl ammonium bromide (CTAB) were used as surfactants in several concentrations and added in the 25wt% NaOH and KOH solutions. It was concluded that the presence of surfactant results in micro-channels with higher removal rates and improved surface quality as shown in Figure 12.

4.4. Effect of tool feed rate

The tool feeding mechanism remarkably affects the machining performance in the SACE process. The selection of tool feed rate should be done effectively as it controls the quality of the machined surface and machining time. It is because feed rates higher than MRR results in the breakage of tools and low feed rates result in higher machining time [83]. In the SACE process, the tool electrode feed rate is controlled by the feeding mechanism adopted for machining. Generally, three feeding mechanisms are available as shown in Table 3.

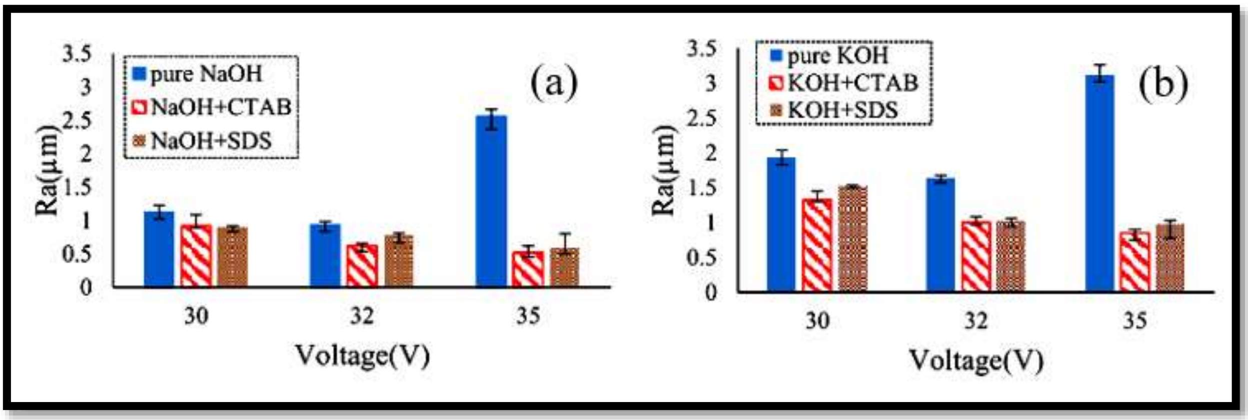

Figure 12: Surface roughness using surfactants (SDS and CTAB) (a) NaOH 25%wt (b) KOH 25 wt% [82].

Table 3 Different tool feeding mechanism in SACE

METHOD	PRINCIPLE	COMMENTS
Gravity feed	Tool motion is obtained by the gravitational force, either tool own weight or additional attached weight to the tool. Permanent contact between the tool and work material.	Forces magnitudes should be minimum as it can break the tool or work material. This method results in more thermal damage of the work material.
Constant velocity	The tool moves at a constant speed in a downward direction. Stepper motors are used to control the tool feed. No permanent contact between the tool and work material.	If tool feed is smaller, machining time is increased. If tool feed is higher, it may result in contact with the work material. Optimum tool feed is selected to maintain the minimum gap.
Adaptive feed control (or Closed-loop feed)	The tool moves according to the actual machining process. It detects contact across the tool and the work material.	The current signal is used as a control parameter to detect the contact and to control the tool motion

4.4.1. Gravity assisted tool feed

Gravity feed is one of the most commonly used tool feed methods in SACE to successfully remove the materials [84-86]. The tool movement is obtained by gravitational forces (either by tool own weight or additional weight attached to it). A constant force always acts between a tool and work material duet to the physical contact. This method produces excellent results n micro-drilling operation but tool breakage is one of the concerns that need to be addressed. Also, more thermal cracks occur at the machined surface due to physical contact. Wuthrich et al. [87] described that machining depth larger than 300 μm is very difficult to achieve using this method due to the lack of electrolyte availability underneath the tool electrode.

4.4.2. Constant velocity tool feed

Another method of tool feeding which is very popular in SACE is the constant-velocity tool feed method. The tool is fed toward the work material at a constant velocity and controlled by using a stepper motor [88-90]. It is possible to maintain a constant machining gap for enabling electrolyte flow and quick gas film formation due to the non-contact between the tool and the work material. However, tool velocity controls the machining gap in this method as very high tool feed results into the tool contact with the work material. It results in the breakage of either tool or work material. This mechanism provides the flexibility of choosing variable speed as its selection is very important in SACE [21]. Didar et. al. [91] examined 2D modeling and characterization of glass during micro-machining with constant tool velocity. It was found that micro-channels with desired surface quality were obtained at an applied voltage lower than 32V and tool speed of less than 30 μm s^{-1} with a working gap of 15 μm. The schematic diagram for gravity feed and constant velocity feed is shown in Figure 13.

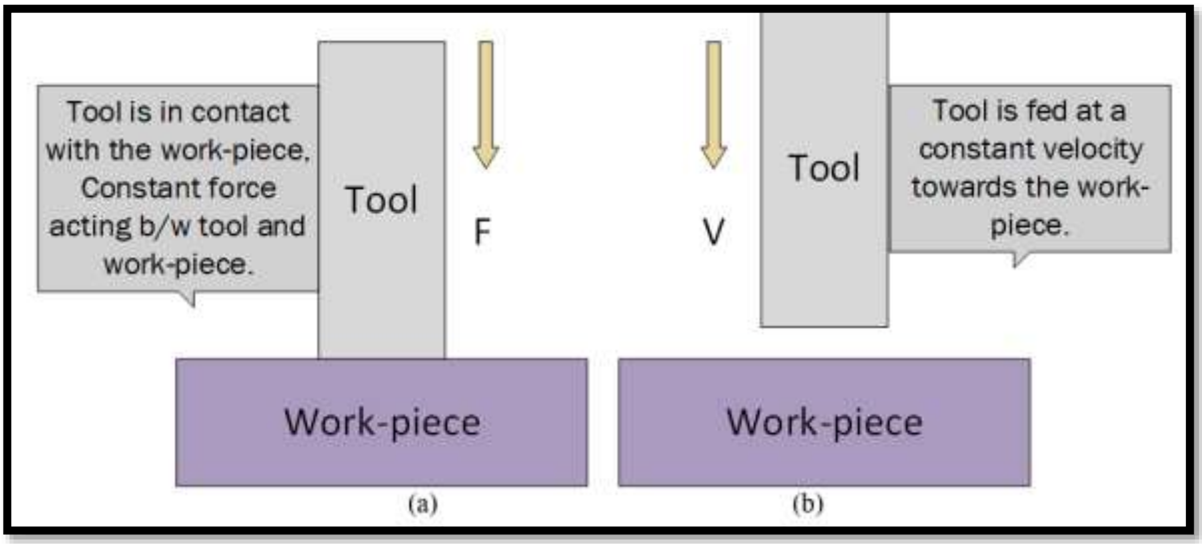

Figure 13: Schematic diagram of different tool feeding mechanism in SACE (a) Gravity feed (b) Constant Velocity feed

4.4.3. The adaptive tool feed system

This is the novel tool feed method and called as adaptive feeding mechanism (or closed-loop mechanism) in which the tool feed is a function of the actual machining process so that a constant gap is retained always between the tool and work material. A minimum machining gap is required to provide the electrolyte underneath the tool electrode for a quick formation of gas film formation. The utilization of force sensors and current signals helps in attaining a closed-loop feeding mechanism by detecting the tool's mechanical contact with the work material. It thereafter takes appropriate action for reversing the tool direction using these current signals [58, 86]. The schematic diagram for the adaptive tool feed control is shown in Figure 14(a).

Cao et al. [58] reported the significance of adaptive tool feed control over gravity feed by utilizing a sensitive load cell. The sensitive load cell produces the potential difference; moment tool comes in contact with the work material. This signal is then forward to a controller via an analog to digital converter. Thereafter, the controller retracts the tool in an upward direction to prevent the contact so that a constant gap is maintained. They set a pre-described value of 8mN for load cell, the moment the contact force increased beyond 8mN then the controller retracts the tool 5 μm in the upward direction to maintain a gap as shown in Figure 14(b). They concluded that the use of a load cell helps maintain a constant gap and small tool immersion depth which further reduces the required critical voltage. High aspect ratio structures were successfully machined with this method.

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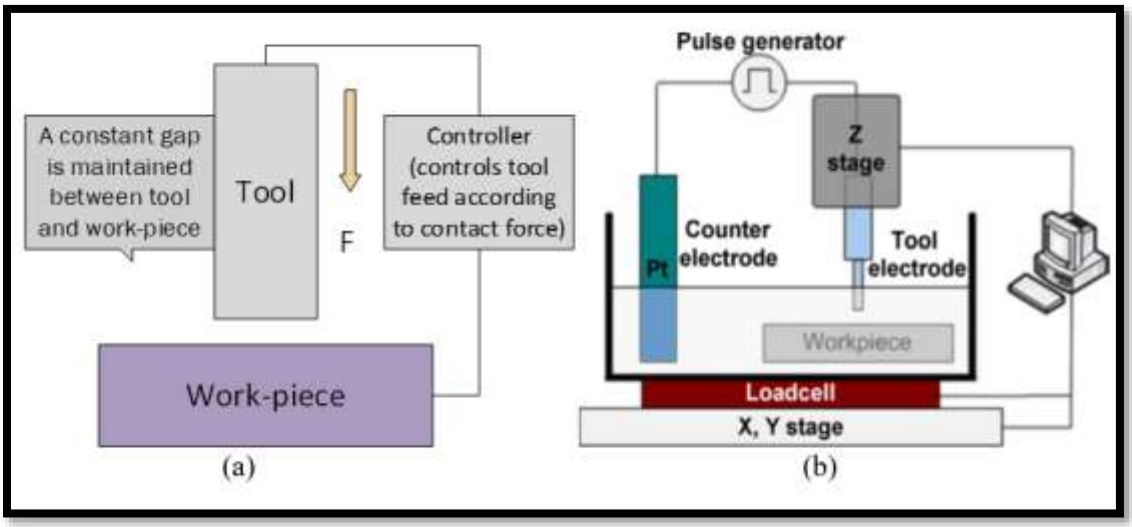

Figure:14(a) Schematic diagram for adaptive tool feed Control; (b) Experimental setup (***Adaptive***) [58]

4.5. Effect of tool geometry

The different shapes of the tool electrode significantly control the spark consistency either uniform discharges or non-uniform discharges which further produces variable machining characteristics [24, 62,84, 87, 92]. Figure 15 illustrates the example of different tool shapes utilized in SACE [51]. Wuthrich et al. [93] critically mentioned that SACE drilling consists of two different regimes: discharge regime (depths < 200 microns) and hydrodynamic regime (higher depths). In the hydrodynamic regime, the flow of electrolyte is the determining factor for controlling the removal rate during mic-drilling. Various tool shapes such as flat side wall [74], a side insulated [92], spherical tool [62], needle-shaped [87], etc. can enhance the electrolyte flow at higher depths and ensure surface quality as well.

Wuthrich et al. [87] have explained that a better spark consistency is achieved using the needle-shaped tool electrode and results in superior surface quality. Moreover, electrolyte flow can be enhanced using tool electrode motions such as vibration, rotation, etc and different tool shapes [84, 87, 93-100].

Yang et al. [62] examined the effect of two different tool geometries i.e., spherical and cylindrical on tool wear and surface roughness. The scanning electron microscopic (SEM) images are shown in Figure 16. The results showed that the spherical tool reduces the tool wear and reduces the machining time by 83% when compared to the cylindrical shape tool.

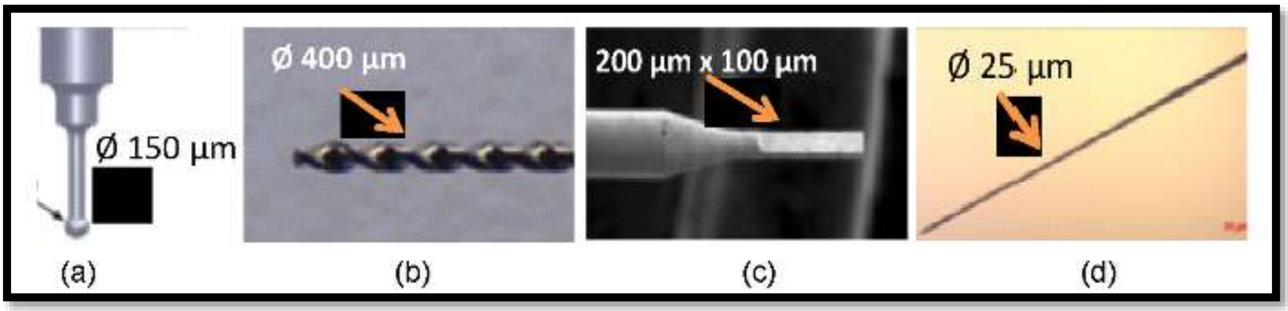

Figure 15: Tool electrode's shapes utilized in SACE (a) Spherical tool (b) Helical tool (c) Rectangular shaped and (d) Cylindrical [51].

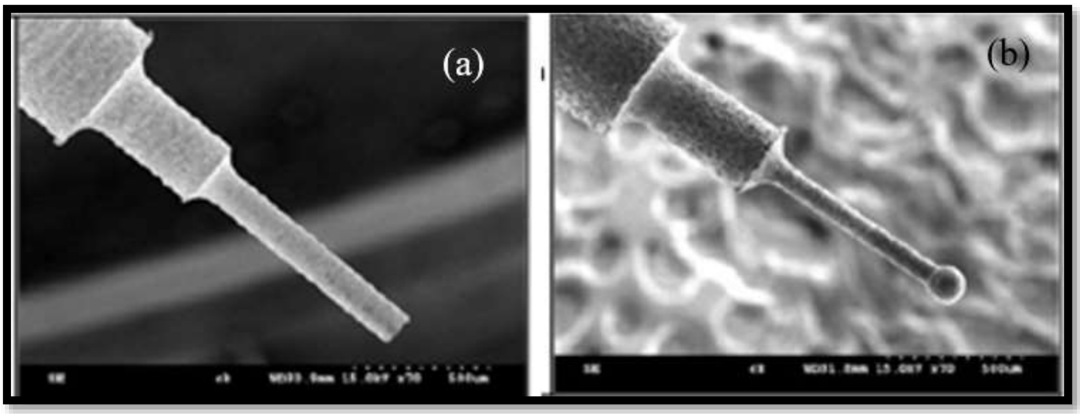

Figure 16: SEM images of cylindrical and spherical tool electrode [62].

4.6. Effect of tool rotation

Tool rotation can improve the geometrical features of the machined surface due to enhancement in electrolyte flow and replenishment. Also, the consistencies are improved with the tool rotation. Improvement in removal rate and surface features can be achieved by providing the rotational effect to the tool electrode [93,95,96,98]. The flow of electrolyte can be improved due to the centrifugal effect created by tool rotation. Tool rotational effect decreases the formation of the stray electrolysis and as a result, reduction in the overcut observed. It produces good quality holes with a precise hole's entrance and exit. Jui et al. [101] concluded that tool rotation improves the hole circularity of the drilled micro-hoes without altering other input parameters. Figure 17 shows the micro-holes comparison with or without tool rotation. Figure 18 shows the summarized report on the tool electrode parameter's effect on SACE performance.

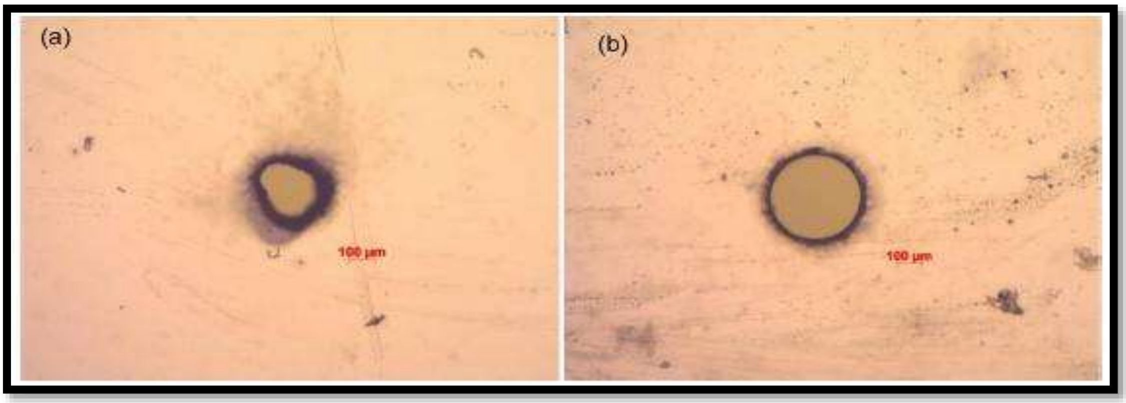

Figure 17: Micro-hole quality with tungsten carbide tool Ø 100–300 μm (a) No tool rotation (b) Tool rotation at 1500 rpm (Work-piece- 200 μm thick glass slide, Electrolyte- NaOH [101].

4.7. Effect of the machining gap

Effective control of the machining gap across the tool and work material can result in various advantages as given below [25, 102-104]

- The stabilized gas film is obtained.
- Optimizing and concentrating the spark behavior underneath the tool.
- Enhance the chemical etching action by enabling the availability of the electrolyte below the tool.

Kulkarni et al. [45] found that the machining gap larger than 600 μm provides insufficient thermal energy at the work material's top surface. Pankaj et al [103] examined the effect of the machining gap on hole overcut by performing experiments. Results revealed that minimum overcut and CURM (Central unremoved material) was obtained when the gap is practically zero. No material removal rate was obtained when the gap is increased beyond 250 μm.

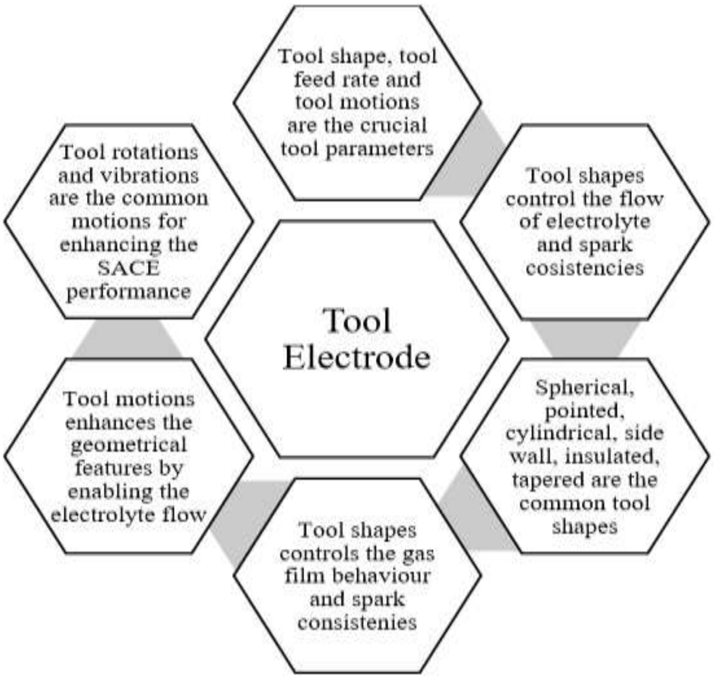

Figure 18: Summarized report on tool electrode parameter's effect on SACE performance.

4.8. Effect of tool immersion depth

In the SACE process, the tool immersion depth critically affects the machining performances by controlling the spark consistencies and gas film stability. Higher tool immersion depths result in the unstabilized gas film formation due to the difficulty in enveloping the whole electrode surface area [104]. It deteriorates the machining performance of the process. Low tool immersion depths produce excellent machining characteristics in terms of surface finish [58, 105-108]. Razfar et al. [106] build up a mathematical model for correlating and optimizing the input parameters alongside tool immersion depth to minimize the HAZ and radial overcut during glass drilling. Three levels of tool immersion depth were selected i.e., 0.9 mm, 1.1 mm, and 1.3 mm for the drilling operation. They observed that higher tool immersion depth reduces the amount of thermal energy transference to the work material. As a result, low HAZ, low MRR, and low ROC were obtained.

4.9. Finite Element Analysis in ECDM Process

Despite experimental investigations, several scholars have attempted and studied the applications of FEM in ECDM to analyze its MRR performance. The goal was to create a transient thermal model based on heat transfer in order to get the temperature distribution. under the impact of a single spark. Earlier studies assumed a uniform cross-sectional heat distribution, however several studies [33-37] used a Gaussian heat distribution for a spark. To get temperature fields, several authors created a FEM model with heat applied to a section of the work material. The final MRR was calculated by integrating around the symmetrical axis [66-69, 109-112]. The predicted results were validated using experimental results and fare consensus was observed between these two.

5. FUTURE RESEARCH POSSIBILITIES

SACE is a highly complicated process and consists of different phenomena. The machining characteristics in SACE majorly rely on process parameters such as voltage, pulse on time, duty cycle, electrolyte type, and its concentration, tool material, tool shape and size, tool feed rate, work material, machining gap, inter-electrode gap (IEG), anode material, etc. To date, the exact material removal mechanism in SACE has not understood well. The contribution of chemical action and its effectiveness is yet to be explored in detail. The major gaps and future scope are highlighted below:

- The different tool feeding mechanism needs to be studied in detail for controlling the tool feed rate so that an effective constant gap is maintained between the work material and the tool. It helps in ensuring the controlled flow of electrolyte between them to establish a stable gas film. Closed-loop system-based machining is yet to be studied in detail.
- It was known that high machining depth in SACE drilling is very challenging due to the lack of electrolyte in the hydrodynamic regime. Higher machining depths with improved machining characteristics are yet to be obtained. Thus, a controlled machining gap with adaptive feed control has to be implied for obtaining higher machining depths with decreased machining time.
- The defects like enlarged hole entrance diameter, high overcut, micro-cracks, high HAZ, tapering are providing new research areas to minimize them.
- Enhancement in MRR is another major scope in the SACE process to make it more pragmatic.

Table 4 highlights the major future areas along with the possible methodology to improve the SACE performance.

Table 4 Research possibilities in SACE process

SACE areas				
MRR	HAZ, Overcut, Micro-cracks	Surface finish	Electrolyte	Tapering effect
Research Possibilities				
Using different combination of Voltage and electrolyte concentration, tool rotation, different tool shapes such as tapered, a side insulated, flat wall side, etc	Study of machining gap, Tool feed rate, and applied voltage.	Selection of different electrolytes for etching action, use of different electrolyte concentration, using different duty ratio	Use of different electrolytes, preheating of electrolytes, Mixing of two electrolytes, environment-friendly electrolytes, abrasive mixed electrolytes.	Use spherical tools, negative taper tools, and rotating tools.
Possible outcomes				
Improvement in MRR	Reduction in HAZ and overcut.	Better surface finish.	Enhancement in surface finish, MRR, and reduction in hazardous effect.	Reduction in tapering effect

6. CONCLUSIONS

The present article discusses the fundamental principles of the SACE process and the input process parameter's effect on its performance. A comprehensive review on SACE determines that its performance majorly relies on the selection of input process parameters. Thus, effective and repeatable machining can be obtained by choosing and optimizing the input parameters.

The present state of art contributes to the existing literature of the SACE by laying down the platform with various research findings on influential parameters (such as electrical parameters, electrolyte parameters, and tool electrode parameters) and their effects on SACE performance. A summarized report on voltage, electrolyte, and tool electrode parameters helps in identifying the critical parameters for pursuing future study with SACE. It further provides the platform for comprehending the mechanism of stabilized gas film formation at the tool vicinity and summarizes the results of crucial parameters affecting gas film stability. The discussions on future visions can be channelized further for enhancing ECDM performance.

The major conclusions withdrawn from the study are given below:

- SACE machining is a novel process for machining the non-conductive material with superior surface quality.
- Thermal models can be successfully applied and utilized to analyze the performance of the SACE process. It helps in predicting the optimized parameters for a certain response.
- Any change in electrolyte conductivity and applied voltage alters the frequencies of the sparks over the work material. Pulse voltage reduces the thermal cracks and HAZ due to the application of periodically sparks (or pulse on time).
- Tool design with an optimum shape such as a pointed tool, flat side tool, tapered tool, etc. can be used for reducing the radial overcut and tapering during micro-drilling at higher depths.
- Closed-loop machining is efficient in maintaining an effective machining gap using a force sensor.
- Appropriate methods of controlling gas film, optimum selection of input parameters, controlling geometrical tolerances, and effective tool feed control system are the critical areas that need continuous improvement and can be further investigated.

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