A Comprehensive Review on Modelingand Simulation Studies in Electro-Chemical Discharge Machining

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Glass has wide application in the production of micro components. Electro-chemical discharge machining (ECDM) has proven an inexpensive and potential micromachining method for such nonconductive materials. ECDM has the electro-chemical machining (ECM) and electric discharge machining (EDM) constituent processes. It overcomes limitations and provides benefits of both constituent processes, namely EDM and ECM. The major limitation in the industrial application of this technique is controlling of gas film formation and discharge activity. Researchers have attempted numerous studies, both experimental and simulation, exploring the physics behind the process. In view of appraising research carried out in recent years, the present work reports a comprehensive review ofmodeling and simulation studies in electro-chemical discharge machining along with a brief introduction to ECDM. Different modeling and simulation approaches applied by researchers were discussed. The importance of various simulation parameters and material removal criteria were justified.

Keywords: Numerical simulation, Modeling, finite element method, Electro-chemical discharge machining, Electrolyte, Material removal rate, Overcut and gas film.

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1 Introduction

Micro and nano machining finds a special place in engineering in the era of advancement in materials and miniaturization. The use of components with micro features (i.e.micro-tools, microsensors, microreactors, dies, nozzles, micro-implants, microchips, and MEMS) are increasing day by day. Industries such as mechanical, automotive, electrical, electronics, optics, biotechnology, communication, defense, biomedical, nuclear, aviation, and space use such components [1], [2]. Glass, ceramic, composite, quartz, Pyrex are widely used nonconductive materials for such micro-products [3]. Production of such micro-devices and micro-systems necessitates micromachining for the generation of required micro-sized features. However, machining such materials by traditional machining methods experiences considerable machinability challenges due to their inherent properties. Excessive tool wear, surface cracks and damages are some of the challenges.

Electric discharge machining (EDM) and electro-chemical machining (ECM) are the two non-conventional machining processes assisted by electrical energy. However,, these two processes are well-established and suitable for electrically conductive materials only. The absence of electrical conductivity in the workpiece limits the use of these two processes [4]. Therefore, electro-chemical discharge machining (ECDM) has emerged as a hybrid process to overcome their limitations, which includes features of both ECM and EDM process [5], [6]. Hybridization of machining processes is an approach to achieve the requisite level of performance in machining with specific workpiece materials.

Researchers have used ECDM for various materials such as glass (i.e., soda-lime glass and borosilicate glass), ceramics (i.e., alumina and silicon nitride), quartz, copper and some composites (i.e., Carbon fiber and Kevlar epoxy composites). ECDM is capable of giving higher machining rates than ECM and EDM alone [7]. In addition, researchers studied and found ECDM performing better regarding material removal, dimensional integrity and surface quality than ECM and EDM alone [8].

Though the process isan economical and potential micro-machining technique, the commercial use of this technology is still limited because of challenges in controlling discharges. Nevertheless, the limitations in the universal commercial acceptance of this technology open up opportunities for further research in this field. This article presents a comprehensive review of modeling and simulation studies reported by researchers in recent years. In addition, a brief introduction of the ECDM process along with its historical development is also described in this section.

The first development of spark-assisted chemical engraving (SACE) was occurred in Japan in the late 1950s for the application in diamond die workshops.Kurafuji and Suda reported ECDMfirst, in the year 1968. A hole was drilled in glass using this process. However, the reason behind the discharge was not clarified. In 1984, Crichton and McGeough reported that bubble formation and growth were responsible for spark generation based on streak photography. However, the cause behind the discharge was still unclarified[3]. The first theoretical model was reported in 1996 by Ghosh et al. Formation of spark was described based on switching theory. In year 1999, Jain et al. described similarities of spark generation to arc dischargein discharge valves and presented the first model of discharge phenomenon, which was based on valve theory.The author applied the finite element method for computing temperature distribution. Since then, various finite element method simulation studies have been published by different researchers.

An electro-chemical cell consisting of two electrodes with grossly different in sizes (about a factor of 100) is a vital part of the ECDM system (refer to Figure 1). The discharge mechanism in ECDM principally depends on the principles of both constituting processes, i.e., ECM and EDM. Initially, the electrolysis process of ECM causes the generation of hydrogen gas on the cathode electrode at a voltage lower than critical voltage. Electro-chemical discharge/sparks occur beyond the application of critical voltage. Workpiece material kept in close proximity to the discharge zone gets machined primarily by melting, vaporization and thermal erosion due to localized heating of work material and simultaneous chemical etching [3], [9].

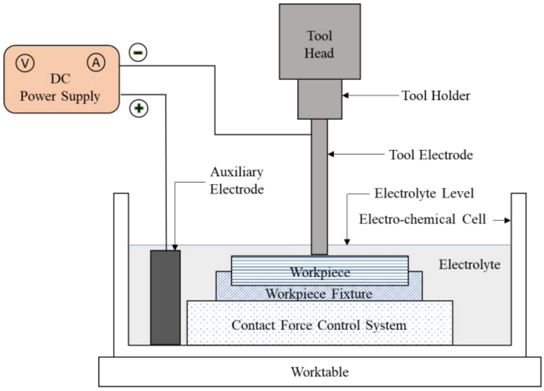

Fig.1 Typical ECDM system.

2 A Comprehensive Review on Modeling and Simulation Studies

Researchers have carried out studies in the field of ECDM involving experimental work, theoretical and simulation studies. This article presents a comprehensive review on modeling and simulation studies carried out by researchers. Finite element-based studies were mostly employed exploring the effects of various parameters. These studies were reviewed and discussed in subsequent sub-sections.

2.1 Theoretical and Analytical Studies

Mc Geough et al. [7]examined the relative effects of electro-chemical and discharge actions in electro-chemical arc machining (ECAM). Theoretically, the influence of voltage, feed rate, the amplitude of vibration and phase difference between voltage and vibration waveforms for metal machining wereanalyzed. The metallic anode workpiece was provided with vibration. The material removal rate (MRR) improved at a higher feed rate, the lower amplitude of vibration, and when voltage (full-wave rectified DC) waveform came closer to the vibration waveform in phase. As a result,ECAM could give higher machining rates than ECM and EDM alone, which could be faster than ECM and EDM by a factor of five and forty times, respectively.

Basak and Ghosh[10] presented a theoretical model for estimating critical electrical parameters (i.e., voltage and current) based on the switching theory. As per switching theory, isolation caused by blanketing of cathode tool with hydrogen gas bubbles and water vapor is responsible for electric discharge (due to switching) between electrode and electrolyte. Changes in values of critical electrical parameters with the concentration of electrolyte were plotted for calculated and experimental values. The machining of electrically conductive material using electro-chemical discharge phenomenon was termed as ECAM and that for non-conductive materials as ECDM. Basak and Ghosh [11] developed another theoretical model based on the switching phenomenon for the prediction of MRR for varying input parameters (concentration, additional inductance and applied voltage). Inductance was identified as another input parameter, which can be controlled easily. Substantial enhancement in machining rate was reported with the introduction of extra inductance in the circuit.Jain et al. [12]highlighted limitations of switching theory and proposed valve theory based on similarities (in terms of voltage and current (V-I) characteristics and values of current and pressure) of spark generation to arc discharge in discharge. Bubbles were modeled as arc discharge valves. According to valve theory, an intense electric field (~ 10 V/µm) produces spark through these bubbles. They computed spark energy and approximate bubble diameter of hydrogen gas.

Wuthrich and Hof [13]reported a lack of reproducibility as a serious weakness of the SACE. A theoretical model was derived to estimate the thickness of the gas film. Reduced gas film thickness resulted in significant improvement in machining repeatability. Several methods for improving the reproducibility of the process were proposed. Low machining voltage and additives that lower the tool electrode's wettability were proposed to reduce gas film thickness. Jiang et al. [14]presented analytical modeling involving bubble growth, evolution and characteristics of the gas film. The range of thickness of gas film estimated from the model (17-29 µm) was consistent with the experimental values. The formation of gas film was filmed with the help of a high-speed camera. It was reported that thin gas filmsare desirable due to lowering critical current and voltage, reducing overcut phenomenon. The current density was reported asa basic parameter for initiating sparks. The generation of bubble and gas film was found proportionally related to current density. Reduced electrode size and immersion depth resulted in higher current density for the same power.

Jalali et al. [15]studied the decrease in drilling speed for micro-hole depth in the range of 200 µmto 300 µm. A model was developed for material removal mechanism considering combining effect of local heating and chemical etching. Out ot the two regimes, the first regime (discharge regime) was observed through the first 200-300 µm depth. The drilling rate was more, as the electrolyte was present.Therefore, material removal was easy. The second regime (hydrodynamic regime) starts deeper in the hole; drilling speed was slow in this regime due to insufficient electrolyte flushing in the machining region. It was concluded that the mechanism of material removal is caused by localized heating and subsequently by chemical etching.

Kamaraj et al. [16]have developed an analytical model explaining the influence of electrolyte concentration on overcut. The model considered chemical etching at high temperature for removal of material during ECDM. Effects of electrolyte concentration and machining time on material removal were described. Machining current and resistance during the process were measured experimentally at varied electrolyte concentrations, which were inputs to the model. Spark was assumed to be initiated from the tool edge. It was concluded from the model that lower concentration is helpful for a reductionin overcut. The machining seemed to attain a steadystate without further increase of the radial overcut. It was reported no significant change inovercutting with tool diameter.

Rajput et al. [17]used the response surface method (RSM).Amathematical modelfor correlating input parameters (i.e., voltage, feed rate and electrolyte concentration) and response parameters (i.e., MRR, tool wear rate, number of tool contacts) was established.

2.2 Finite Element Method (FEM) Studies

The finite element method is a widely used and powerful tool used in research, especially while carrying out simulation studies. Numerous FEM-based studies relating to ECDM reported in the literature were reviewed and presented in sub-sections of this part of the article.

2.2.1 Studies on Effect of Electrical Parameters

Jain et al. [12]appliedthe finite element method for computing temperature distribution based on the unsteady-state heat conduction equation in three dimensions. Randomly located sparksof the square cross-section with uniform heat flux were considered. Temperature contours were used for estimating overcut, limited depth of penetration, and material removal per spark. An increasing trend of MRR, overcut, and depth with supply voltage was presented. Results were compared graphically with Basak'sexperimental results.

Bhondwe et al. [18]obtained temperature distribution using the finite element method (FEM) considering a single spark, which was further processed for prediction of MRR for soda-lime glass and Al2O3 workpieces during electrochemical spark machining (ECSM). Gaussian heat flux was considered in the thermal model. Temperature distribution along radius and depth were presented for alumina and soda-lime glass (temperature at the surface was of the order of 13500-17000 K). An increasing trend of MRR with concentration of electrolyte, pulse duty factor and energy partition was observed based on their parametric study.

Jiang et al. [19] determined the energy of spark experimentally and fit into a model to reveal electro-chemical characteristics of two different tool electrodes. A FEM model was established to relate the energy of spark with geometry of the material removed. The simulation results exhibited high current densities at tool tip and edges.Which was further validated bythe fringing effect (distributionof spark surrounding the rim) that existed for the cylindrical tool. In contrast, the needle-shaped tool has simply one location of spark generation. The tapered tool was found to have a higher current density and more consistent in spark generation than the cylindrical tool. The average spark energy was determined 3.8 milli Joule at 34 Volts electrode voltage.

Paul and Korah[20] developed a thermal model to determine the influence of different types of power sources (direct current and pulsed DC) on MRR during the ECDM process. ECDM with pulsed DC was found better than continuous DC with reduced temperature and improved MRR for Borosilicate glass. In addition, improved tool life and lower HAZ were observed in pulsed DC due to intermittent cooling during pulse off time.

Goud and Sharma [21] have developed a 3DFEM model for simulating material removal in electro-chemical discharge drilling for soda-lime glass and Al2O3 workpieces. Gaussian distributed heat flux inside the spark was considered in the model. Graphically, the temperature distribution within the work domain and material removal variation with input parameters (voltage and concentration) were presented. Similar increasing trends of simulation and available experimental results were observed.

Mishra et al.[22] demonstrated numerical simulation and fabricated microchannels on the glass substrate. Machining voltage, pulse frequency and tool feed rate were considered as process parameters for analyzingsurface roughness (SR) and MRR of the microchannels as response parameters. Experimental results exhibited an increasing trend of SR and MRR with increasedtool feed rate and machining voltage, whereas the decreasing trend of MRR was observed with increasing pulse frequency. The capability of ECDM process was demonstrated by fabricating sinusoidal microchannel and engraving letters on the glass substrate.Mishra et al.[23]also fabricated microchannels using ECDM based multi-pass micro-milling. They carried out numerical simulationsfor predicting the shape and size of the microchannel. A higher rate of tool wear was observed at increased machining voltages. For deep micromachining applications on glass, a moderate level of machining voltage and pulse frequency with higher electrolyte concentration were recommended. Results obtained with pulsed power were found better than DC (continuous) power supply. Channel depth increased with machining voltage and concentration of electrolyte.However, they also reported increased tool wear at high machining voltages.

Sharma et al.[24] reported deep micro-holes (425 µm) fabrication in Al2O3 substrate using ECDM process. Increased machining voltage resulted in higher energy of discharge. Therefore, higher consumption of tool. At the same time, increasing tool feed rate resulted in reduced tool wear. A decrease in the micro-hole depth was reported with increasing machining voltage because of a drastic change in tool dimension (due to higher discharge energy at higher voltages), which tends to increase the tool work gap. Overcut increased with an increasing machining voltage. A numerical simulationfor estimating crater depth showed an increasing trend with machining time similar to experimental results.

Rajput et al. [17] presented a FEM-based thermal model for obtaining temperature distribution and computing MRR in electro-chemical discharge drilling. Parametric studies were carried out using simulation results for studying the effect of machining parameters,i.e., voltage, type of electrolyte, electrolyte concentration and energy partition on MRR of silica glass. Improvement in MRR was observed with increasing voltage, electrolyte concentration and energy partition. Tool feed rate was found to be the most governingprocess parameter for controlling tool wear rate (TWR) and number of tool contacts (NTC), whereas applied voltage was found the most dominant process parameter for controlling MRR.

2.2.2 Studies on Effect of Electrolyte Parameters

Bhondwe et al. [18] reportedan increasing trend for MRR with increasedelectrolyte concentration, based on their parametric study using finite element simulation.Goud and Sharma[21]presented temperature distribution in workpiece and variation in material removal with electrolyte concentration, graphically based on 3D finite element simulation of ECDM drilling for soda-lime glass and alumina workpieces.

Kolhekar and Sundaram [25] have carried out multi-phase FEM simulation and experimentation for understanding the influence of gas film on overcut in ECDM. Electrolyte evaporation during the process was simulated by considering a multi-phase fluid system (i.e., gas and liquid). Thermal variations in the electrolyte's viscosity, density, and heat capacity were taken care ofin simulating the variation of buoyancy and convection effects due to temperature change. A function was defined for providing input to the system based on energy, frequency and random distribution of sparks. Nusselt number was increasedwith increasing level of electrolyte, which explains that increase in electrolyte level, heat transfer due to convection dominates. The thicker and more unstable gas film formationwas reported with an increase in electrolyte level and produced more radial overcut and hole taper. Thin gas film resulted in a higher depth of cut, which is a preferable choice for making through-hole.

Electrolyte selection is crucial because it controls spark patterns and is also responsible for flushing debris away from the machining zone. Rajput et al.[26]developed a thermal model for studying the effects of different electrolytes (viz. NaOH, KOH, and NaCl) on MRR. The effects of applied voltage, electrolyte concentration, spark radius, and duty ratio were also analyzedon soda-lime glass through simulation. Experiments showed that the use of NaOH produced higher MRR as compared to KOH and NaCl at 60% wt. concentration. It was found that KOH provided better results in terms of overcutting and circularity because of smooth and stable spark. It was concluded that NaOH and KOH were successful electrolytes for machining using ECDM.

2.2.3 Studies on Miscellaneous Parameters

The energy partitiondissipated to workpiece also affects the simulation results., An increasing trend of MRR with fraction of energy transferredwas reportedby Bhondwe et al. [18]based on their parametric study.Wei et al. [27] reported that the process performance during ECDM drilling varies with depth. Two regimes were classified based on the depth of drilling, as discharge regime (< 300 μm depth) and hydrodynamic regime (> 300 μm). A FEM based model was presented for simulating material removal by a solo spark in the discharge regime. The fraction of thermal power transmitted to the workpiece was reported 29.1% and maximum machinable depth was estimated as 303 μm.

Krotz et al. [28] carried out experimentation and simulation on heat flux into the anodic metal workpiece (100Cr6 Steel) with single discharge approach in micro electro-chemical arc machining (μ-ECAM). The plasma formation at the cathode was recorded with a high-speed camera. Plasma temperature was determined as 3500 K (based on emission spectroscopy). Heat source was modeled as a disc-shaped area (diameter of 10 μm) in the simulation model. The recast layer thickness was reported 3μm and 2.9μm, based on experimental and simulation results, respectively.

Behroozfar and Razfar[29] presented a FEM based thermophysical model for characteristics of plasma channel and material removal in ECDM of soda lime glass. The plasma channel's mean diameter was reported as 260 μm based on spark signatures. The average diameter and depth of craters were reported 200 μm and 22 μm, respectively. Material removal, diameter and depth of crater were determined and compared experimentally.

Hajian et al.[30] presented FEM-based thermal model for predicting machining depth in electro chemical discharge milling. Different machining voltages and electrolyte concentrations were used for calculating input parameters to FEM model. Gaussian heat flux distribution and random location of sparks were considered in the simulation. Softening Littleton point (720 °C) as a material removal criterion was recommended for soda-lime glass based on a comparison of simulation and experimental results.

Mishra et al.[22]presented the trend for variation of MRR with tool feed rate asincreasing based on simulation and experimental results. For electro-chemical discharge drilling (ECDD) of silica glass, Rajput et al. [17] reported that the tool feed rate was the most governingprocessparameter for controlling TWR based on RSM analysis.

Arab et al.[31]fabricated array of through-holes in silica workpiece (400 μm thickness). The machined hole's depth was estimated using FEM-based numeric simulation, which was validated experimentally.

Elhami and Razfar[32]presented a model considering the distinct constitutive phenomenon of discharge (plasma). Various phenomena considered in the simulation were electromagnetic field, electric current and heat transfer in solid and liquid. Based on literature and satisfying arc discharge conditions and localized thermal equilibrium, plasma was modeled in the simulation, assuming as fluid. Mode of single discharge was applied and results were computed depth and material removal. It was reported that a maximum temperature value of 3650°C is attainable in plasma column. However, regions nearer to the tool were reported at a temperature lower than regions close to the workpiece.

Arab et al.[33] reported the influence of tool-substrate gap on ECDM performance with two different electrolytes (KOH and NaOH). Simulation and experimental results exhibited a decreasein depth of blind hole with the increasing tool-substrate gap. Arab et al.[34]inspected the influence of initial tool-workpiece gap on blind hole formation and tool wear in velocity-feed in ECDD, with varying electrolyte concentration and machining time. Numerical model was developed with inverse heat flux reduction for changing tool-workpiece gap. The results of experiments were compared with that of numerical study. The micro-holes depth was found maximum without a gap; however, drastic tool wear was observed in this condition. Different ranges of optimal gap of 10 μm to 30 μm and 5 μm to 20 μm was reported for NaOH and KOH electrolytes, respectively for glass workpiece.

2.2.4 Simulation Approaches and Parameters

This section summarizes the parameters and modeling approaches used by researchers in their simulation studies. Researchers have carried out simulations using two-dimensional as well as three-dimensional models,which are summarised in Table 1. Different approaches of heat source modeling were used in previous studies, such as the application of heat flux and applying temperature on workpiece top surface. Heat flux has been applied on workpiece top surface as a heat source in most of the previous studies.Krotz et al. [28]applied the temperature on work domain surface as heat source.Kamraj et al. [16]considered point heat source at tool edge in their analytical study.

Uniform heat flux and Gaussian distribution heat flux within spark have been used by different researchers is given in Table 2.The use of Gaussian distribution heat flux was common. Spark cross-section has been considered as circular by researchers. However, researchers have considered square cross-section spark in early research[12], [35]. Taking a circular cross-section spark in study is common. Constant, as well as varying spark radius, has been considered by different researchers as given in Table 3. The duration of spark has been considered 100 μs by researchers in their studies. Spark duration depends on the pulse on time when pulsed power is employed which is given in Table 4.

Researchers have carried out studies on different workpieces such as glass, alumina [18], [21], [24] and steel [28]. Owing to wide applications of glass, most of the studies employed glass as workpiece. Although most of the studies were based on drilling operation, very few simulation studies were carried out for microchannel and milling operation [22], [23], [30].

Energy partition factor influences simulation results. Researchers have used different values of energy partition of the total heat energy imparted to the workpiece,which is summarised inTable 5. Material removal criterion is another factor that also influences simulation results. Various material removal criteria were used by different researchers,which are tabulated in Table 6.

Table 1. Simulation models used in finite element studies by different researchers

Simulation model	Researcher(s)	Year
Two-dimensional	Bhondwe et al. [18]	2006
	Wei et al. [27]	2011
	Krotz et al. [28]	2013
	Jiang et al. [19]	2014
	Kamraj et al. [16]	2015
	Behroozfar and Razfar[29]	2016
	Paul and Korah [20]	2016
	Kolhekar and Sundaram [25]	2019
Three-dimensional	Goud and Sharma [21]	2017
	Hajian et al. [30]	2018
	Mishra et al. [22]	2019
	Mishra et al. [23]	2019
	Arab et al. [31]	2019
	Sharma et al. [24]	2020
	Rajput et al. [26]	2020
	Arab et al. [33]	2020
	Rajput et al. [17]	2020
	Arab et al. [34]	2021

Table 2. Heat flux distribution within spark

Heat flux distribution	Researcher(s)	Year
Uniform	Jain et al. [12]	1999
	Kolhekar and Sundaram [25]	2019
Gaussian	Bhondwe et al. [18]	2006
	Wei et al. [27]	2011
	Jiang et al. [19]	2014
	Behroozfar and Razfar[29]	2016
	Paul and Korah [20]	2016
	Goud and Sharma [21]	2017
	Hajian et al. [30]	2018
	Mishra et al. [22]	2019
	Mishra et al. [23]	2019
	Arab et al. [31]	2019
	Sharma et al. [24]	2020
	Rajput et al. [26]	2020
	Arab et al. [33]	2020
	Rajput et al. [17]	2020
	Arab et al. [34]	2021

Table 3. Spark radius used by different researchers

Spark radius	Researcher(s)	Year
150 μm	Bhondwe et al. [18]	2006
	Wei et al. [27]	2011
	Jiang et al. [19]	2014
	Goud and Sharma [21]	2017
	Mishra et al. [22]	2019
	Mishra et al. [23]	2019
	Arab et al. [31]	2019
	Rajput et al. [26]	2020
	Arab et al. [33]	2020
	Rajput et al. [17]	2020
	Arab et al. [34]	2021
130 μm (based on experiment)	Behroozfar and Razfar[29]	2016
$0.788*T_{on}^{0.75}$ where, T_{on}=pulse on time	Sharma et al. [24]	2020
$2040*I^{0.43}*t_d^{0.44}$ where, I=current and t_d=discharge on time	Kolhekar and Sundaram [25]	2019

Table 4. Spark duration used in by different researchers.

Spark duration	Researcher(s)	Year
100 μs	Wei et al. [27]	2011
	Goud and Sharma [21]	2017
	Hajian et al. [30]	2018
	Rajput et al. [26]	2020
	Rajput et al. [17]	2020
Pulse on time	Behroozfar and Razfar[29]	2016
	Mishra et al. [23]	2019
	Sharma et al. [24]	2020
	Arab et al. [33]	2020
	Arab et al. [34]	2021

Table 5. Energy partition factor considered by different researchers

Energy partition factor	Researcher(s)	Year
5%	Goud and Sharma [21]	2017
	Mishra et al. [22]	2019
	Mishra et al. [23]	2019
	Sharma et al. [24]	2020
	Arab et al. [33]	2020
	Arab et al. [34]	2021
10%	Arab et al. [31]	2019
20%	Bhondwe et al. [18]	2006
	Rajput et al. [26]	2020
	Rajput et al. [17]	2020
29.1%	Wei et al. [27]	2011
	Jiang et al. [19]	2014
	Behroozfar and Razfar[29]	2016
	Hajian et al. [30]	2018

Table 6. Material removal criteria used by various researchers in simulation studies

Researchers	Criteria for MR	Value
Jain et al. [12]	Softening of Soda lime glass and Borosilicate glass	850 °C & 820 °C
Fascio et al. [35]	Glass softening temperature	About 920 °C
Bhondwe et al. [18]& Goud and Sharma [21]	Melting temperature of soda lime glass and alumina	1400 °C & 1827 °C
Wei et al. [27]& Jiang et al. [19]	Equivalent temperature for soda lime glass	600 °C

Researchers	Criteria for MR	Value
Kamraj et al. [16]	Machining temperature	Temperature rise of 200 °C above room temperature
Hajian et al. [30]	Recommended softening Littleton temperature for soda lime glass	720 °C
Rajput et al. [17]	Melting point of quartz	1670 °C
Mishra et al. [22]	Melting temperature of glass substrate	1400 °C
Behroozfar et al. [29]	Assumed critical temperature of glass	600 °C

3 Future Research Scope

This research article comprehensively reviews different researchers' modeling and simulation studies during the last two decades. Literature review revealed that maximum research had been carried out considering a single spark. However, the single spark approach has some limitations. Compounding errors in computing material removed in a specific time duration based on a single discharge study is one of the limitations of this approach. Each spark does not provide the same heating effect. Hence, different quantities of material removal take place by each spark. The quantity of material removed by a single discharge also depends on surface topography. This can be understood by considering two different cases: flat surface and surface having depression/cavity experiencing similar heating effects at the spark strike location, resulting in different quantities of material removal. Thus different approach close to reality needs to be developed.

It is evident from the literature that knowledge on energy partition to the workpiece and ejection efficiency are insufficient. Further, the values of these parameters also vary with different machining conditions such as electrolyte type, electrolyte temperature, workpiece material and tool feed rate. Research to obtain more knowledge on energy partition factor and ejection efficiency will help to attain closeness to the actual discharge phenomenon.

One of the major applications of micromachining is fabricating microchannels for microfluidic devices. The literature revealed that most modeling and simulation studies were only sticking to the drilling or hole-making operation. A very few researchers have attempted for simulation of microchannel fabrication using ECDM. Hence, the scope for modeling and simulation studies is open in this direction.

4 Conclusions

Electro-chemical arc machining process is a hybrid micro-machining process that provides advantages for ECM and EDM processes. It is capable of machining at faster rates than each of the constituent processes.

Researchers have carried out theoretical and analytical modeling s for estimation of spark and response characteristics such as spark energy, approximate hydrogen gas bubble diameter, gas film thickness,MRR and overcut.

Most of the FEM based research has been executed based on the simulating effect of single spark that is too limited to the drilling operation.Different approaches like the constant temperature approach, point (tool-tip) heat source approach, uniform and Gaussian distribution of heat flux within the spark approach have been used to model the single spark heat source in simulation studies. Critical spark parameters such as spark radius and duration of spark do not remain constant throughout the process. Thus, these spark parametersneed to be correlated with experiments for achieving closeness to actual discharge activity.

Various parameters such as the fraction of total energy imparted to the workpiece (or energy partition) and ejection efficiencies also significantly affect the accuracy of simulation outcomes. Hence, more knowledge of these parameters is vital.

Material removal occurs primarily due to the thermal effect of electro-chemical discharge followed by chemical etching. Researchers have considered different material removal criteria like softening temperature, melting temperature, equivalent temperature, machining temperature, critical temperatureand softening Littleton temperature of workpiece material. Material removal criteria directly influence the computed MRR. Therefore, the selection of material removal criteria is very crucial.

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