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A critical review on different types of Tools used in ECDM Process

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Abstract
SACE (Spark Assisted Chemical Engraving) or ECDM (Electro Chemical Discharge Machining) is an interesting micro m/c technique, reported by Kurafuji and Suda, in 1968. It is a non- conventional machining method preferred in micro-machining non conducting or semi conducting materials; particularly, hard to machine materials like glass, ceramics, composites etc. The Tool used in ECDM one of the important factor in improving machining characteristic. Through this paper an extensive review has been made and reported on tool modification, enhancements and up-gradation and it has been found that profiles and rotary tools are much popular for micro machining and higher accuracy point of view.

Key words: Micro machining, rotary tools, profiled tools, insulated tools, Batch electrode.

I. Introduction

The mechanism of ECDM is a blend of ECM (Electro Chemical Machining) and EDM (Electro Discharge Machining) capable of machining hard non conducting material. The basic working principle is explained as follows: The working material, machining tool (tool electrode) and counter electrode are dipped into an appropriate electrolytic solution. Generally the tool electrode is taken as cathode and counter electrode as anode. On applying voltage, hydrogen gas bubbles and oxygen gas bubbles starts forming on cathode and anode respectively. The Current density increases by increasing terminal voltage which results in increased number of gas bubbles with larger mean diameter. After reaching a certain voltage i.e critical voltage (25V) gas bubbles get coalesced and form gas film around the electrode and the discharge (sparking) occurs. Due to the discharge material removal takes place by the phenomenon of melting and evaporation along with high temperature chemical etching.

There are number of process parameters involved in the process, mainly “voltage and applied current”, “electrolyte”, “feed rate”, “tool specifications and “tool electrode gap”. The discharge occurs at critical voltage which depends on electrolyte and tool geometry. Bhattacharyya et al. [1], have reported that bubbles start generating at 25V and low spark discharge take place around 40V; however, effective machining occurs at 70-90V. They have concluded that with increase in voltage, the MRR also increases. At higher voltage ($\geq$ 90V) micro cracks on work surface are observed. Dae-Jin Kim et al. [2] have used series of rectangular voltage pulse, instead of full wave DC voltage and concluded that better surface finish with less heat affected zone can be obtained by using high frequency and less duty ratio but with low MRR. The gas film thickness is also an important parameter. Wutthrich et al. [3] have reported that the decrease in gas film thickess results in lower critical voltage .The most commonly used electrolyte in ECDM are NaOH , KOH, $NaNO_3$, Nacl. Sabahi et al. [4] have found by adding surfactant (CTAB, SDS) in electrolyte changes physicochemical properties of electrolyte and tool electrode wettability which in result decrease the gas film thickness, increased microchannel’s depth , improved geometric and surface quality, less HAZ and increased MRR by more chemical etching ; Sabahi et al. [5] have concluded that by using mixed electrolyte (NaOH+KOH) in equal proportions improved surface quality and more electrical conductivity than KOH and NaOH separately can be obtained. Han et al. [6] have used powder (graphite powder) mixed electrolyte and found better surface integrity.

Tool workpiece gap is an important parameter to be controlled for effective machining. Gupta et al. [7] have reported that for better machining minimum working gap is desirable and was no material removal when working gap exceeds 250µm. To maintain constant minimum working many researchers used Gravity feed mechanism; however Goud et al. [8] have reviewed gravity feed method which leads to tool distortion or bending for microtools, wear of tool electrode . Gautam and Jain [9] have used constant velocity feed rate which ranges from 0.002-1.2 mm/min (achived with the help of stepper motor and reduction gear arrangement) .Singh and Dvivedi [10] have used pressurized feeding mechanism with the help of compression springs to maintain constant working gap (almost negligible) and found 207.4% improvement in machining depth with less complicated setup because it does not require any feedback system to control motion . Yi Xu et al. [11] employed counter resisting feeding method to increase repeatability of process as compare to conventional gravity feed method. As the depth of machining increases contact force between tool and workpeice decreases leads to better electrolyte flow. Hajian et al. [12] have studied relationship between tool bending force and feed rate. He observed that larger bending force which leads to breakage of tool can be avoided by employing slow feed rate and this optimum feed rate value can be increased by applying higher voltage and higher electrolyte concentration.

II. Research findings on utilization of different tools and their kinematics for enhancing ECDM :

A. Using rotary effect on tools:

Gautam et al. [13] were the first to employ rotational effect to the tool electrode. Two types of rotations were given to the electrode first about its own axis with the help of a stepper motor and the other one was an eccentric rotation with the help of a special slider type tool mechanism in which the eccentricity was controlled by changing offset between spindle axis and tool axis. They stated that due to the tool rotation scavenging effect on electrolyte was observed which in turn had enhanced the machining rate; however, higher RPM had adverse effect on machining performance hence they used low rpm. With an increase in eccentricity (nearly about tool radius)the machining depth was increased after that it started decreasing. Jui et al. [14] had found that through the tool rotations, better circularity of machined holes can be produced. Huang et al. [15] have studied the effect of rotation on tool wear and found that with an increase in rotation speed, the tool wear had decreased. Harugade et al. [16] have employed high speed rotation to tool in Electrochemical Discharge Engraving. They concluded that higher MRR and less overcut had observed with increased tool rotation speed. Kozak et al. [17] established mathematical models to study performance characteristics of rotary ECDM. Wei et al. [18] have used rotating micro drills and observed that direction of rotation also influenced the MRR. The electrolyte with pressure reached to the machining area through the rotating reverse spiral and promoted material removal. Pawar et al. [19] have conducted experiments and concluded that tool rotation had least significance for the machining depth and diametric cut as compared to voltage and electrolytic concentration. Dafade and Waghmare [20] applied taguchi method and concluded that MRR was influenced by applied voltage, tool roation, tool workpiece gap with 60, 36.91, 2.17 percentage respectively.

B. Using Surface textured tools:

Han et al. [21] explained that conventionally micro ECDM uses cylindrical micro-electrode in which intensified electric field and concentrated spark discharge was at the bottom edge , discharge at tool side wall was very less and it could be improved by applying higher voltage but had negative impact on the surface integrity and produced large HAZ . They generated micro protrusion patterns by using EDM and after that it was electrochemically etched for five seconds to remove EDM by products .The surface roughness value of tool increased .These asperities promotes spark discharge and lowered the critical voltage, using tool texturing localized electric field intensification effect helped in improving ECDM milling depth with high geometric accuracy. Yang et al. [22] studied the effect of surface roughness of tool and stated that surface roughness was related to the wettability of the tool. Greater the surface roughness meant larger the contact angle which resulted in poor wettability , poor wettability causing thicker gas films to be formed leading to larger diameters. Singh and Dvivedi [23] observed that MRR and depth was improved by 19.27 and 64.81 percent respectively due to textured tool.

C. Tools with vibration effect:

Elhami et al. [24] used cathode tool integrated with ultrasonic vibration and have reported decrease in the gas film thickness. The amplitude of Vibration has an inverse relationship with the gas film thickness. Upto 10μm amplitude, the most uniform current signal was obtained, above 10μm excessive turbulence in gas films and electrolyte lead to undesirable effects. Wuthrich et al. [25] employed vibration to the tool electrode with the help of voice -coil actuator for drilling at different amplitude and frequency and concluded that frequency did not had significant effect, while the Amplitude had a significant effect. After certain depths the amplitude of vibration helped the electrolyte to flow but after certain value much larger amplitude lead to a larger difference in heat the source at workpiece end and experimentally upto 50% reduction in machining time was found for the amplitude value of 10 μm. Pawariya et al. [26] investigated ultrasonic assisted Electrochemical Discharge Trepanning. Tool was provided with ultrasonic vibration. They have observed that vibration had expelled debris and replenished electrolyte. They have also concluded that energy channelization index had increased by ten times. Rusli and Furutani [27] observed that ultrasonic vibration affected gravity feed ECDM drilling in three ways, changed discharge behavior, improved electrode circulation and tool electrode to workpiece collision. Razfar et al. [28] compared square and sinusoidal vibration waveform and observed that upto 40% increased machining depth when square waveform voltage, upto 20% increased machining depth when sinusoidal waveform voltage, had employed to the actuator.

D. Rotating tools coated with abrasives.

This is also known as “grinding aided electrochemical discharge machining” (G-ECDM). Chak and Rao. [29] have used rotating abrasive tools and have proved abrasion as one of the material removing mechanism , which helps in removing recast layer and it also increased the machining rate by providing additional discharge at bottom of tool surface because of the gap created by the projected length of active abrasive particle. They have also concluded that orbital motion provided to rotating abrasive electrode resulted in increased MRR [30]. Liu et al. [31] used diamond reinforced rotating tool, found ten times decreased surface roughness and three times higher MRR. Ladeesh and Manu [32] developed FEA model to find effect of parameters on edge chipping thickness. In G-ECDM edge chipping occured due to thermal stress of the discharge and mechanical stress due to thrust force applied by the tool. They found that edge chipping thickness can be decreased with an increase in support length and also by decreasing the voltage and pulse on time. They have also concluded that in Electrochemical Discharge Cross Peripheral Grinding average profile surface roughness and average areal surface roughness values were increased with an increased voltage, inductance, electrolyte concentration and tool feed rate [33], increased electrolyte temperature in GECDM led to increased MRR [34] and high duty ratio (above 0.6) associated with high frequency led to thermal cracks on workpiece in GECDD [35]. Liu et al. [36] observed that tool is less clogged in G-ECDM as compared to only grinding operation due to discharging effect.

E. Insulation on Tools:

Han et al. [37] used side insulated tools to generate more stable sparks. They stated that irregular sparks due to the randomness of gas film formation by using conventional ECDM tool caused thermal damage i.e micro cracks with larger HAZ. The insulation added to electrode localized electrolysis and generated stable and uniform gas film by inducing single bubble formation. Partial insulation resulted in machining with good surface finish (decreased surface roughness value). Tang et al. [38] have used diamond coated full side insulated electrode for drilling of holes. They found more accuracy in shapes by reducing the taper angle with lesser entrance diameters.

F. Different tool shapes:

Jain et al. [39] used travelling wire driven by stepper motor as a tool and found that it is feasible and effective process for slicing large volume materials. Complex shapes on workpiece were also reported formed. Furutani et al. [40] used WC deposited saw wire as a tool and concluded that depth of machined groove increased as compare to conventional wire tool. Wang et al. [41] used daimond saw wire of 0.2 ± 0.01mm diameter to cut alumina. They have concluded that initially surface roughness had been increasing and then slightly decreased on applying higher voltage , very less amount of recast layer was found that too on higher voltage. Liu et al. [42] have used rotating helical tool in wire ECDM and studied effect of machining parameters on side gap in slicing of glass workpiece. They observed that side gap had been following increasing trend with increase in voltage and duty factor, and decreasing trend with increase in frequency, spindle speed and feed velocity. Rattan et al. [43] employed magnetic field to Wire ECDM and found increased MRR in the range of 9.09 - 200%.Wang et al. [44] have proposed oil film assisted Wire ECDM which provided greater stability to insulating film on tool wire. Mehrabi et al. [45] used hollow tool electrode employed with high pressure electrolyte injection through it which resulted in increased MRR and drilling speed because of proper availability of electrolyte at higher depths. Arya et al. [46] investigated that electrolyte flow rate through the hollow electrode is dependent on thermal energy provided in the machining zone in pressurized flow ECDM. Bhattacharyya et al. [1] have investigated effect of different tool tip geometrical shape on machining rate and accuracy. They have used three shapes first and found MRR with taper side wall and curvature front > taper side wall and flat front > straight side wall and flat front because taper side wall and curvature front provide more electrolyte flow and overcut follows trend of straight side wall and flat front > taper side wall and curvature front > taper side wall and flat front because stray sparking is more in case of straight side wall and flat front as compare to other two configurations. Zheng et al. [47] compared conventional cylindrical tool with flat side wall and flat front tools made by WEDG (wire electro discharge grinding) process. They reoorted better machining accuracy with flat side wall and flat front tools due to less discharge at tool side walls. Yang et al. [48] compared cylindrical tool tip with spherical tool tip. They have reported better electrolyte flow due to reduced contact area in spherical tool, spherical tool electrode enhanced machining performance and shape accuracy. The Machining time is also reduced by 83% as compared to the cylindrical tools for a depth of 500µm.Saranya et al. [49] concluded reduction by 84% in hole entrance diameter using spherical tool tip .

G. Batch / Array tool:

Guo et al. [50] have used Focused -Ion-Beam Chemical Vapour Deposition to fabricate Corner, Pillar and Array types of 3D nanoelectrodes for ECDM .Skrabalak et al. [51] used batch electrode ie multielectrode to increase process productivity . Batch electrode made by using two processes first one is by using wire EDM (electro discharge machining) and the second one is SLS (selective laser sintering). The electrodes made by SLS contained holes which enabled the electrolyte to flow through tips. Due to better flushing of electrolyte in working gap better working efficiency and accuracy was observed in case of SLS tools which were considered best for machining large no of holes. The wire cut electrode had better side wall surface finish as compare to SLS electrode which caused higher taper angles when SLS electrode is used. Arab et al. [52] formed through holes with the stainless steel array tool electrode fabricated with wire EDM. They reported that longer tool tips had resulted into continuous sparking and better results were founded with KOH over NaOH electrolyte.

M M Goud et al. [8] reviewed different types of tool electrode material and found Tungsten Carbide is widely used as tool electrode because of its high wear resistance, high temperature resistance and chemical inertness . Other than tungsten carbide ,stainless steel copper, brass, ms with abrasive coating have been used in the order tungsten carbide > stainless steel > copper > brass > ms with abrasive coatings. Some researchers also used molybdenum as tool electrode. M Mousa et al. [53] conducted experiments using electrode with different thermal conductivity and concluded that for discharge regime material with higher conductivity results in higher machining rate whereas for hydrodynamic regime material with higher conductivity resulted in slower machining rate in gravity feed micro drilling .

Ziki et al. [54] compared tool wear rates and thermal expansions for tungsten , steel and stainless steel tool and found tool wear rate in the order tungsten > steel > stainless steel , and thermal expansion in the order of stainless steel > steel > tungsten. Behroozfar et al. [55] investigated effect of voltage on different tool materials .They concluded that voltage at which tool errosion had started depended upon the type of tool material and its melting point, In case of brass , steel and tungsten, the tool wear started at about 46, 48 and 53Volts respectively. Pawar et al. [56] concluded that Tool Wear Rate in highly influenced by Voltage followed by electrolyte concentration and roation. Zhang et al. [57] conducted experiments with solution of different conductivity and concluded that tool wear rate and conductivity of solution follows inverse relation. The figure 1, illustrates various methods and innovations in using tools in SACE/ECDM. Table 1 illustrates various types of tools used along with their applications and researchers who have reported them.

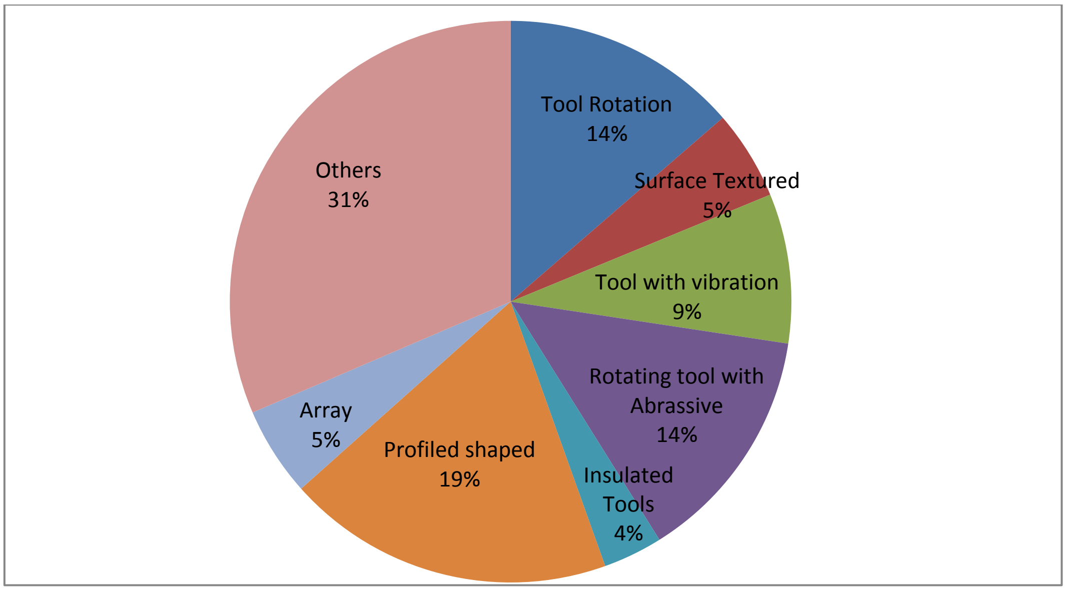

Figure 1: Various types of tools used in ECDM process

Table 1: Various tools and their applications

Type of Tool	**Specific application**	**Tool Material used**	**Reported by**
Rotating Tool	Drilling	Tungsten Carbide	Jui et al. [14]
	Drilling	Tungsten Carbide	Huang et al. [15]
	Engraving	Tungsten Carbide	Harugade et al. [16]
	Drilling	Tungsten Carbide	Wei et al. [18]
	Drilling	Brass	Pawar et al. [19]
	Drilling	Copper	Dafade and Waghmare [20]
Surface Textured Tool	Microgrooving	Brass	Han et al. [21]
	Drilling	Stainless steel, Tungsten, Tungsten carbide	Yang et al. [22]
	Micro-channels	Stainless Steel (304)	Singh and Dvivedi [23]
Tool with Vibration	Drilling	Stainless Steel	Wuthrich et al. [25]
	Trepanning	High Speed Steel	Pawariya et al. [26]
	Drilling	Tungsten	Rusli and Furutani [27]
	Drilling	Tungsten Carbide	Razfar et al. [28]
Rotating Tool with Abrasive	Drilling	Brass (Diamond abrasive)	Chak and Rao. [29]
	Drilling	Iron based Hollow cylinder Ni coated (Diamond abrasive)	Lui et al. [31]

	Drilling	Diamond cored Drill bit	Ladeesh and Manu [32]
	Peripheral Grinding	Diamond cored Drill bit	Ladeesh and Manu [33]
	Grinding	Steel drill [Diamond grit]	Lui et al. [36]
Insulated Tool	Pocket Milling (micro channel)	Tungsten Carbide	Han et al. [37]
	Drilling	Tungsten Carbide	Tang et al. [38]
Wire Shaped	Slicing	Brass Wire	Jain et al. [39]
	Slicing	Steel core Saw Wire covered With Tungsten Carbide layer	Furutani et al. [40]
	Slicing	Steel core Saw Wire with Diamond Grits fixed by Electroplated Nickel layer .	Wang et al. [41]
	Micro channel	Tungsten Carbide	Liu et al. [42]
	Slicing	Brass Wire	Rattan et al. [43]
	Micro Slit	Molybdenum Wire	Wang et al. [44]
Hollow Tool	Drilling	Brass	Mehrabi et al. [45]
	Drilling	Stainless Steel (SS-304)	Arya et al. [46]
Tools with varied tips	Drilling	Copper	Bhattacharyya et al. [47]
	Drilling	Tungsten Carbide	Zheng et al. [48]
	Drilling	Tungsten Carbide	Yang et al. [49]
	Drilling	Tungsten Carbide	Saranya et al. [50]
Array Tools	Surface structuring Upto desired depth	stainless steel 316L / 1.4404 (C – 0.03%, Ni– 11.5%, Mn – 2.0%, Cr – 17.5%, N – 0.11%, Mo – 2.3%).	Skrabalak et al. [52]

III. **Conclusions:**

The paper illustrates review on various tooling used in ECDM. Through the critically conducted literature review, it has been found that:

- Profiled shaped tools are most widely used followed by rotational tools (rotating tools and abrasive coated rotary tools).
- Insulated tools are least used followed by array and surface textured tools.

Continuous research in this field is still being carried out and opportunities exist in-terms of improving the repeatability and accuracy, especially in micro-machining thereby making it suitable for production at industrial levels. Using LIGA (a combination of lithography, Galvanoformung and Abformung, which is basically a X-ray lithography technique), FIB-CVD (Focused-Ion-Beam Chemical Vapor Deposition), SLS (Selective Laser Sintering), Wire EDM etc., and many other rapid prototyping techniques, array of tools can be manufactured more precisely.

REFERENCES:

1. Bhattacharyya, B., Doloi, B. N., & Sorkhel, S. K. (1999*). Experimental investigations into electrochemical discharge machining (ECDM) of non-conductive ceramic materials*. Journal of Materials Processing Technology, 95(1-3), 145-154.
2. Kim, D. J., Ahn, Y., Lee, S. H., and Kim, Y. K. (2006*). Voltage pulse frequency and duty ratio effects in an electrochemical discharge microdrilling process of Pyrex glass*. International Journal of Machine Tools and Manufacture, 46(10), 1064-1067.
3. Wüthrich, R., and Hof, L. A. (2006). *The gas film in spark assisted chemical engraving (SACE)—a key element for micro-machining applications*. International Journal of Machine Tools and Manufacture, 46(7-8), 828-835.
4. Sabahi, N., Razfar, M. R., and Hajian, M. (2017*). Experimental investigation of surfactant-mixed electrolyte into electrochemical discharge machining (ECDM) process*. Journal of Materials Processing Technology, 250, 190-202.

5. Sabahi, N., and Razfar, M. R. (2018). *Investigating the effect of mixed alkaline electrolyte (NaOH+ KOH) on the improvement of machining efficiency in 2D electrochemical discharge machining (ECDM)*. The International Journal of Advanced Manufacturing Technology, 95(1-4), 643-657.
6. Han, M. S., Min, B. K., and Lee, S. J. (2007). *Improvement of surface integrity of electro-chemical discharge machining process using powder-mixed electrolyte*. Journal of Materials Processing Technology, 191(1-3), 224-227.
7. Gupta, P. K., Dvivedi, A., and Kumar, P. (2014). *A study on the phenomenon of hole overcut with working gap in ECDM.* Journal of Production Engineering, 17, 30-34.
8. Goud, M., Sharma, A. K., and Jawalkar, C. (2016). *A review on material removal mechanism in electrochemical discharge machining (ECDM) and possibilities to enhance the material removal rate*. Precision Engineering, 45, 1-17.
9. Gautam, N., and Jain, V. K. (1998). *Experimental investigations into ECSD process using various tool kinematics*. International Journal of Machine Tools and Manufacture, 38(1-2), 15-27.
10. Singh, T., and Dvivedi, A. (2018*). On pressurized feeding approach for effective control on working gap in ECDM*. Materials and Manufacturing Processes, 33(4), 462-473.
11. Xu, Y., Chen, J., Jiang, B., and Ni, J. (2018). *Investigation of micro-drilling using electrochemical discharge machining with counter resistant feeding*. Journal of Materials Processing Technology, 257, 141-147.
12. Hajian, M., Razfar, M. R., and Etefagh, A. H. (2017). *Experimental study of tool bending force and feed rate in ECDM milling*. The International Journal of Advanced Manufacturing Technology, 91(5-8), 1677-1687.
13. Gautam, N., and Jain, V. K. (1998*). Experimental investigations into ECSD process using various tool kinematics*. International Journal of Machine Tools and Manufacture, 38(1-2), 15-27.
14. Jui, S. K., Kamaraj, A. B., and Sundaram, M. M. (2013). *High aspect ratio micromachining of glass by electrochemical discharge machining (ECDM)*. Journal of Manufacturing Processes, 15(4), 460-466.
15. Huang, S. F., Liu, Y., Li, J., Hu, H. X., & Sun, L. Y. (2014*). Electrochemical discharge machining micro-hole in stainless steel with tool electrode high-speed rotating*. Materials and Manufacturing Processes, 29(5), 634-637.
16. Harugade, M. L., Waigaonkar, S. D., Mane, N. S., & Hargude, N. V. (2017). *Effect of High-Speed Tool Rotation on Electrochemical Discharge Engraving*. In Proceedings of 10th international conference on precision, Meso, Micro and Nano engineering, Copen (Vol. 10, pp. 4-7)..
17. Kozak, J., and Zybura, M. (2012). *Mathematical modeling of rotary electro chemical discharge machining (RECDM)*. In Proceedings of the World Congress on Engineering and Computer Science (Vol. 2).
18. Wei, C., Ni, J., and Hu, D. (2010). *Electrochemical discharge machining using micro-drilling tools*. Transactions of NAMRI/SME, 38, 105-111.
19. Pawar, P., Kumar, A., and Ballav, R. (2018). *Parametric study of electrochemical discharge drilling on ceramic material using Taguchi method.* Journal of Mechanical and Energy Engineering, 2.
20. Dafade, S. V., and Waghmare, C. A. (2015). *Optimization of Process Parameters in Electrochemical Discharge Machining (ECDM)*. Journal of Basic and Applied Engineering Research, 2(16), 1339-1343.
21. Han, M. S., Chae, K. W., and Min, B. K. (2017*). Fabrication of high-aspect-ratio microgrooves using an electrochemical discharge micromilling process*. Journal of Micromechanics and Microengineering, 27(5), 055004.
22. Yang, C. K., Cheng, C. P., Mai, C. C., Wang, A. C., Hung, J. C., and Yan, B. H. (2010). *Effect of surface roughness of tool electrode materials in ECDM performance*. International Journal of Machine Tools and Manufacture, 50(12), 1088-1096.
23. Singh, T., and Dvivedi, A. (2018). *On performance evaluation of textured tools during micro-channeling with ECDM*. Journal of Manufacturing Processes, 32, 699-713.
24. Elhami, S., and Razfar, M. R. (2017). *Study of the current signal and material removal during ultrasonic-assisted electrochemical discharge machining*. The International Journal of Advanced Manufacturing Technology, 92(5-8), 1591-1599.
25. Wüthrich, R., Despont, B., Maillard, P., and Bleuler, H. (2006*). Improving the material removal rate in spark-assisted chemical engraving (SACE) gravity-feed micro-hole drilling by tool vibration*. Journal of Micromechanics and Microengineering, 16(11), N28.
26. Pawariya, K., Dvivedi, A., and Singh, T. (2019). *On performance enhancement of electrochemical discharge trepanning (ECDT) process by sonication of tool electrode*. Precision Engineering, 56, 8-19.
27. Rusli, M., and Furutani, K. (2012). *Performance of micro-hole drilling by ultrasonic-assisted electro-chemical discharge machining*. In Advanced Materials Research (Vol. 445, pp. 865-870). Trans Tech Publications.

28. Razfar, M. R., Behroozfar, A., and Ni, J. (2014). *Study of the effects of tool longitudinal oscillation on the machining speed of electrochemical discharge drilling of glass*. Precision Engineering, 38(4), 885-892.
29. Chak, S. K., and Rao, P. V. (2008). *The drilling of Al 2 O 3 using a pulsed DC supply with a rotary abrasive electrode by the electrochemical discharge process.* The International Journal of Advanced Manufacturing Technology, 39(7-8), 633-641.
30. Chak, S. K., and Rao, P. V. (2014). *Machining of SiC by ECDM process using different electrode configurations under the effect of pulsed DC*. International Journal of Manufacturing Technology and Management 4 and 25, 28(1-3), 39-56.
31. Liu, J. W., Yue, T. M., and Guo, Z. N. (2013*). Grinding-aided electrochemical discharge machining of particulate reinforced metal matrix composites*. The International Journal of Advanced Manufacturing Technology, 68(9-12), 2349-2357.
32. Ladeesh, V. G., and Manu, R. (2018). *Effect of machining parameters on edge-chipping during drilling of glass using grinding-aided electrochemical discharge machining (G-ECDM).* Advances in Manufacturing, 6(2), 215-224.
33. Ladeesh, V. G., and Manu, R. Electrochemical Discharge Cross Peripheral Grinding (ECD-CPG) of borosilicate glass and its performance evaluation.
34. Ladeesh, V. G., and Manu, R. (2019). *Grinding-aided electrochemical discharge drilling in the light of electrochemistry*. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 233(6), 1896-1909.
35. Ladeesh, V. G., and Manu, R. (2016*). Grinding aided electrochemical discharge drilling (G-ECDD) of borosilicate glass and its performance evaluation*. Procedia Technology, 25, 1122-1128.
36. Liu, J., Lin, Z., Yue, T., Guo, Z., and Jiang, S. (2018). *An analysis of the tool electrode working mechanism of grinding-aided electrochemical discharge machining of MMCs*. The International Journal of Advanced Manufacturing Technology, 99(5-8), 1369-1378
37. Han, M. S., Min, B. K., and Lee, S. J. (2008). *Modeling gas film formation in electrochemical discharge machining processes using a side-insulated electrode*. Journal of Micromechanics and Microengineering, 18(4), 045019.
38. Tang, W., Kang, X., and Zhao, W. (2017). *Enhancement of electrochemical discharge machining accuracy and surface integrity using side-insulated tool electrode with diamond coating*. Journal of Micromechanics and Microengineering, 27(6), 065013.
39. Jain, V. K., Rao, P. S., Choudhary, S. K., and Rajurkar, K. P. (1991). *Experimental investigations into traveling wire electrochemical spark machining (TW-ECSM) of composites.* Journal of Engineering for Industry, 113(1), 75-84.
40. Furutani, K., and Tomoto, M. (2008). *Combination Machining of Wire-sawing with Electro-chemical Discharge Machining.* In ASPE Proceedings 23rd Annual Meeting.
41. Wang, J., Guo, Y. B., Fu, C., and Jia, Z. (2018). *Surface integrity of alumina machined by electrochemical discharge assisted diamond wire sawing*. Journal of Manufacturing Processes, 31, 96-102.
42. Liu, Y., Zhang, C., Li, S., Guo, C., and Wei, Z. (2019). *Experimental Study of Micro Electrochemical Discharge Machining of Ultra-Clear Glass with a Rotating Helical Tool*. Processes, 7(4), 195.
43. Rattan, N., and Mulik, R. S. (2017). *Improvement in material removal rate (MRR) using magnetic field in TW-ECSM process.* Materials and Manufacturing Processes, 32(1), 101-107.
44. Wang, J., Fu, C., and Jia, Z. (2018). *Research on oil film-assisted wire electrochemical discharge machining*. The International Journal of Advanced Manufacturing Technology, 1-7.
45. Mehrabi, F., Farahnakian, M., Elhami, S., and Razfar, M. R. (2018). *Application of electrolyte injection to the electro-chemical discharge machining (ECDM) on the optical glass.* Journal of Materials Processing Technology, 255, 665-672.
46. Arya, R. K., and Dvivedi, A. (2019). *Investigations on quantification and replenishment of vaporized electrolyte during deep micro-holes drilling using pressurized flow-ECDM process*. Journal of Materials Processing Technology, 266, 217-229.
47. Zheng, Z. P., Su, H. C., Huang, F. Y., and Yan, B. H. (2007). *The tool geometrical shape and pulse-off time of pulse voltage effects in a Pyrex glass electrochemical discharge microdrilling process*. Journal of Micromechanics and Microengineering, 17(2), 265.
48. Yang, C. K., Wu, K. L., Hung, J. C., Lee, S. M., Lin, J. C., and Yan, B. H. (2011). *Enhancement of ECDM efficiency and accuracy by spherical tool electrode*. International Journal of Machine Tools and Manufacture, 51(6), 528-535.

49. Saranya, S., and Sankar, A. R. (2015, March). *Effect of tool shape and tool feed rate on the machined profile of a quartz substrate using an electrochemical discharge machining process*. In 2015 2nd International Symposium on Physics and Technology of Sensors (ISPTS) (pp. 313-316). IEEE.
50. Guo, D., Wu, X., Lei, J., Xu, B., Kometani, R., and Luo, F. (2016). *Fabrication of micro/nanoelectrode using focused-ion-beam chemical vapor deposition, and its application to micro-ECDM.* Procedia CIRP, 42, 733-736.
51. Skrabalak, G., & Stwora, A. (2016*). Electrochemical, electrodischarge and electrochemical-discharge hole drilling and surface structuring using batch electrodes*. Procedia CIRP, 42, 766-771
52. Arab, J., Mishra, D. K., Kannojia, H. K., Adhale, P., & Dixit, P. (2019*). Fabrication of multiple through-holes in non-conductive materials by Electrochemical Discharge Machining for RF MEMS Packaging*. Journal of Materials Processing Technology.
53. Mousa, M., Allagui, A., Ng, H. D., and Wüthrich, R. (2008). *The effect of thermal conductivity of the tool electrode in spark-assisted chemical engraving gravity-feed micro-drilling.* Journal of Micromechanics and Microengineering, 19(1), 015010.
54. Ziki, J. D. A., and Wüthrich, R. (2012). *Tool wear and tool thermal expansion during micro-machining by spark assisted chemical engraving*. The International Journal of Advanced Manufacturing Technology, 61(5-8), 481-486.
55. Behroozfar, A., and Razfar, M. R. (2016). *Experimental study of the tool wear during the electrochemical discharge machining*. Materials and Manufacturing Processes, 31(5), 574-580
56. Pawar, P., Ballav, R., and Kumar, A. *Material removal and tool wear analysis by ECDM drilling of a mosaic ceramic material.*
57. Zhang, C., Xu, Z., Hang, Y., and Xing, J. (2019). *Effect of solution conductivity on tool electrode wear in electrochemical discharge drilling of nickel-based alloy*. The International Journal of Advanced Manufacturing Technology, 1-14.