Experimental investigation on the stability of electro chemical discharge machining (ECDM)

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ABSTRACT

KEYWORDS

TGV,
Stability,
Probability Chart,
I-MR Chart,
EDS.

Through Glass Vias (TGV) are preferred over Through Silicon Vias (TSV) for 5G wireless transmission because of their non-conducting nature, which lowers the losses. Due to the limitations of current methods, ECDM is an evolving method for micromachining glass. ECDM is a hybrid machining process, encompassing the characteristics of electro discharges and electrochemical machining. But in the hydrodynamic regime, bubble buildup and sludge formation in the micro-machining zone degrade the ECDM's ability to channel energy. Additionally, the presence of a thermal gradient (produced by thermal discharges) encourages the thermal diffusion of the electrolyte and steadily raises its temperature, which destabilizes the process and hampers its commercial viability. In the present communication, a study on the stability of ECDM process has been conducted by using Shewhart control charts (I-MR Chart) with Probability plots. Outcomes from the control charts witnessed an unstable state of the ECDM process. Subsequently, possible causes are identified, and remedial action has been suggested for future work.

1. Introduction

Tremendous applications of micro level products l Micro Electro Mechanical Systems (MEMS), micro fluidic chip, Through Vias, Watch components, Smart phone glass cover etc. are gaining huge attention (Dario et al., 2000; Judy, 2001). Electrical insulation, thermal stability, chemical resistance, and biocompatibility are just a few of the beneficial characteristics that glass offers that are helpful in micro-fluidic, lab-on-a-chip, and MEMS applications. Through Silicon Vias (TSV), which cause significant losses in the high frequency transmissions necessary for the upcoming 5G wireless transmissions, are caused by silicon's semiconductor nature. Thus, Through Glass Vias (TGV) is a new paradigm for Radio Frequency Micro Electromechanical Systems (RF-MEMS) to lower the transmission losses in the upcoming 5G wireless transmission due to its non-conducting nature, transparency, and chemical inertness (Kumar et al., 2020). Glass's poor machinability prevents its use in MEMS (Wüthrich & Fascio, 2005). Industries are currently using non-conventional machining processes including Laser Beam Machining (LBM), Ultra Sonic Machining (USM), and Abrasive Jet Machining (AJM), among others, to achieve the goals of industry. Polymers, ceramics, and metals are machined with LBM using thermal energy. But the need for expensive machinery and the Heat Affected Zone (HAZ) restrict LBM's industrial usefulness. Regardless of their electrical conductivity, mechanical energy-based procedures like USM and AJM can produce intricate microfeatures on hard and brittle materials (Cheema et al., 2015), but their use is restricted due to their inability to process ductile materials. Although chemical energy-based machining technologies provide intricate microprofiles on a variety of materials with outstanding surface finish, their drawbacks include limited dimensional accuracy, slow processing, and low aspect ratio. A machining method that can manufacture micro features over a variety of work materials, regardless of material strength, hardness, and conductivity, is desperately needed in light of these limitations. These conditions allow for the development of Kura Fuji's electrochemical discharge machining (ECDM) in the 1968. This process has meticulously machined several advanced materials like: (i) glass, (ii) composites

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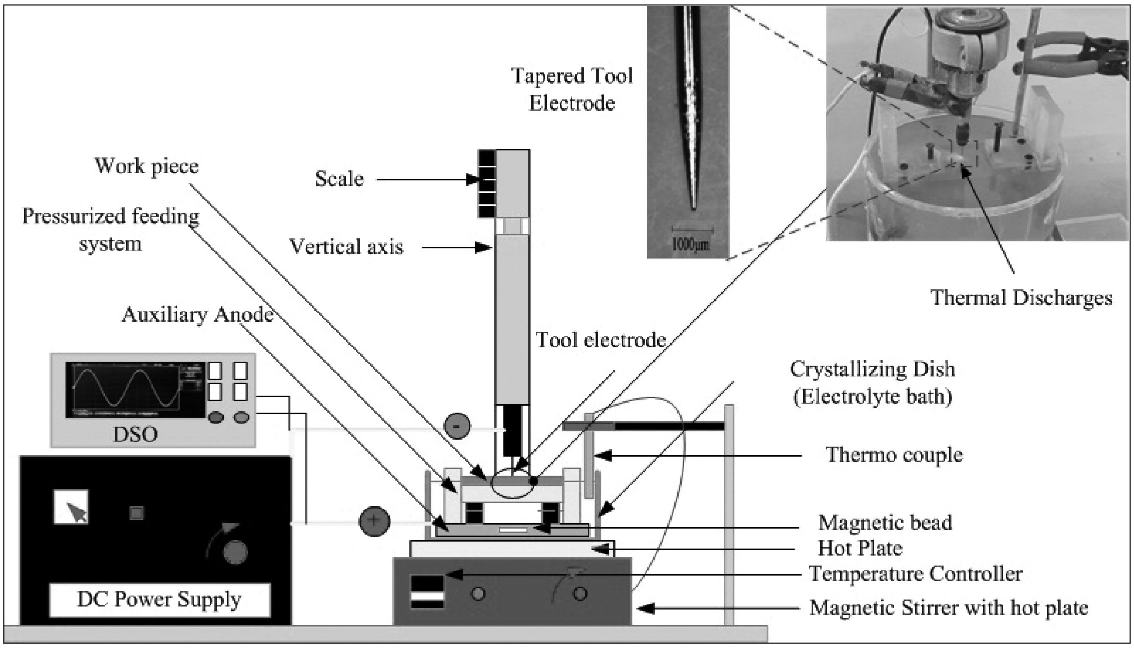

Fig. 1. Schematic of ECDM setup.

(Jha et al., 2019), (iii) ceramics (Bhattacharyya et al., 1999), (iv) ceramics (Singh et al., 1996), (vi) E-glass–fiber–epoxy composite material (Malik & Manna, 2016) (vii) silicon wafer (Singh et al., 2020), (viii) Zirconium oxide (Doloi et al., 1999). In the past few decades, ECDM has become a preferred micro-machining technique for working with glass materials (Behroozfar & Razfar, 2016). Fig.1 displays a schematic representation of the ECDM setup.

The voltage across the cathode and anode of an electrochemical cell (ECC) formed by a DC power source produces hydrogen and oxygen bubbles at the cathode and anode, respectively, as a result of electrochemical processes. (Weier & Landgraf, 2013):

$$At\ Cathode: \quad 4H_2O + 4e^- \rightarrow 2H_2 + 4(OH)^- \qquad \text{.................(1)}$$

$$At\ Anode: \quad 4(OH)^- \rightarrow 2H_2O + O_2 + 4e^- \qquad \text{.................(2)}$$

$$Sum: \quad 2H_2O \rightarrow 2H_2 + O_2$$

The gas film forming mechanism is primarily responsible for the machining mechanism in the ECDM process. The hydrogen gas bubbles physically collide with one another, merge to form a huge gas bubble, and then surround the tool electrode in a hydrogen gas layer (Bhattacharyya et al., 1999). The gas film is formed by the coalescence of the electrochemically formed bubbles (Wüthrich & Fascio, 2005) and also by the local evaporation of electrolyte due to Joule heating (Allagui & Wüthrich, 2009; Kolhekar & Sundaram, 2018). Bubble accumulation around the tool electrode enhances the resistance in the gap of gas bubbles, resulting in the increase of temperature by joule heating and consequently, gas film formation takes place due to vaporization (Society, 1950). Increase in electrolyte temperature increases its conductivity, which accelerates formation of gas film by the electrolysis process as well as evaporation. Interestingly, it is reported that in ECDM, gas film contains extra elements than just hydrogen (Wüthrich & Fascio, 2005). Particularly when NaOH or KOH is used as the electrolyte, ions of potassium or sodium are observed. These ions' presence in the gas film can be a key element in thermal discharges. A high electric field (107 V/m) is created by the hydrogen gas film insulation surrounding the tool electrode. This electrical breakdown of the dielectric film results in thermal discharges, which bombard the work piece with a large number of electrons, causing intense heating, melting, and ultimately material removal (Kulkarni et al., 2002). At the same time, due to elevated temperature, the chemical etching gets accelerated and causes material removal (Fascio et al., 2003). the material removal rate due to etching is given by the following eq. (3) (Jalali et al., 2009).

$$m = 3 \times 10^7 exp\left(-\frac{6571.3}{T}\right) \qquad \text{.................(3)}$$

Here, m indicates the MRR (mg/hr/unit area). According to this equation etching rate increases

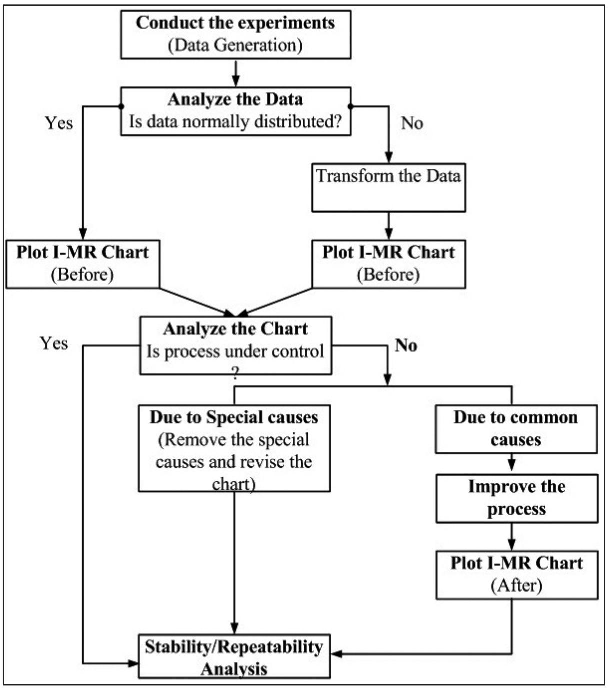

Fig. 2. Planned layout of the study.

Table 1
Process parameters for ECDM.

Parameters/materials	Value
Work piece material	Borosilicate Glass
Electrolyte	NaOH (15 wt%)
Applied voltage	45V
Electrolyte level	2 mm
Tool electrode	SS 304 [Cylindrical (diameter = 500 um)]
Machining time	2 min
Inter Electrode Gap (IEG)	43 mm

with temperature. Perhaps, this is attributed to the reason of decreasing viscosity of glass at elevated temperature. Literature reveals that stability of the gas film is a crucial factor to improve the performance of ECDM process. To stabilize the gas film, numerous hybridization techniques are reported in the literature (Singh & Dvivedi, 2016). However, it was observed that ECDM process does not maintain the stability throughout machining due to variation in electrolyte temperature during machining and thermal gradient in the electrolyte bath. By virtue of this temperature gradient a concentration gradient builds up in the fluid until system reaches in steady state (Rahman & Saghir, 2014). So due to temperature and concentration of electrolyte, ECDM process exhibits variation in the performance characteristics. In literature, ECDM process has been levelled as a stochastic process (Goud & Sharma, 2017). However, in author's knowledge no study has been carried out on the control and stability of the ECDM process. Therefore, in the present communication, an attempt has been made to analyze the control and stability of ECDM process by using Individual-Moving Range (I-MR) charts with probability plots.

2. Materials and Methods

The Advanced Manufacturing Processes (AMP) laboratory at IIT Roorkee was used to design the ECDM facility setup for the current investigation (Fig. 1). The experimental set-up consists of a DC power source, a crystallizing dish composed of borosilicate glass, a pressured feeding system (work fixture), a micro tool electrode, an auxiliary electrode (Anode), etc. The auxiliary electrode was connected to the power source's positive terminal, while the tool electrode was attached to the negative terminal. Due to its high temperature resistance and chemical inertness, borosilicate glass was chosen as the work material; its mechanical and chemical characteristics were taken into account from the literature (Kumar & Dvivedi, 2019). A dedicated pressurized work feeding system has been used to hold and feed the workpiece, having an equivalent stiffness of 0.973 N/mm. Using the pressurized feeding system is intended to keep the minimal consistent working gap (nearly nil) throughout the machining process, which lowers performance variance.

2.1. Methodology

In this section, a set of 38 experiments (micromachining of holes) was carried with the process parameters tabulated in Table 1. Dimensional analysis of the machined micro holes was carried out using dial gauge (Make: Mitutoyo, Model: 2109S-10P, least count). Subsequently, I-MR chart was employed to assess the control and stability of the process.

Shewhart control charts are widely used for statistical process control in various industrial process (Kuo et al., 2017; Tai et al., 2013). An I-MR chart gives insights into process variation with respect to time in a graphical method, which helps in the identification of out-of-control process along with a focus for sources of assignable causes. In order to monitor the process performance statistically, the control charts have been used extensively (Tai et al., 2013). Kuo

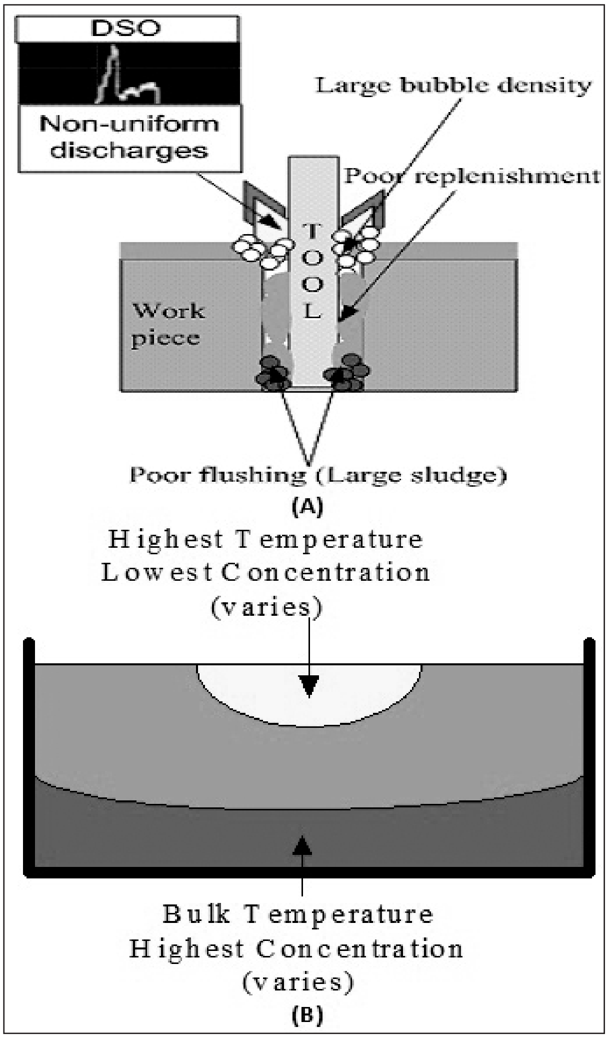

Fig. 3. Process mechanism of ECDM process.

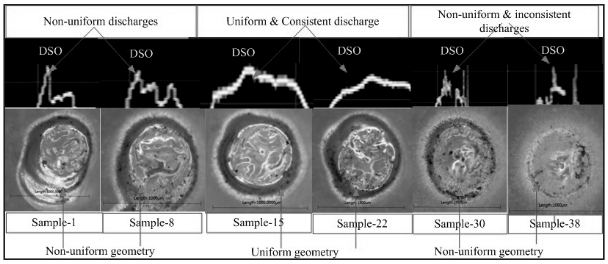

Fig. 4. Transformation of discharge behavior during machining of 38 samples in a sequence.

utilized the probability plots for the normality of the data and constructed I-MR Charts in EDM process to explore the stability and repeatability (Kuo et al., 2017). Tai et al. (2013) employed Shewhart control chart with probability plots in EDM process to analyze the stability of the process. Ahmed et al. (2018) employed Shewhart type I-MR charts with RSM to assess the surface roughness of samples produced by ECM. The planned layout of the present study is demonstrated in Fig. 2.

3. Results and Discussions

In ECDM, as machining progresses deeper into microholes the accumulation of hydrogen bubbles and sludge in the machining zone hampers the replenishment of electrolyte in the machining zone (Fig. 3A). Moreover, the electrolyte temperature continuously rises during machining as a result of the continuous transfer of energy by thermal discharges, which enhances the electrolyte's conductivity (Le Bideau et al., 2019) and lowers the critical voltage (Paul & George, 2018). Additionally, the thermal diffusion caused by the thermal gradient and ongoing increase in electrolyte temperature causes change in the electrolyte concentration, as seen in (Fig. 3B). Owing to these reasons, the behavior of gas film changes with respect to machining depth as well as machining time, which percolate into the discharge behavior and consequently, on the performance of the process as shown in Fig. 4. As the electrolyte temperature increases from 25 to 42 °C and the critical voltage decreases from 23 volts to 22.5 volts throughout the micromachining of the first 8 samples, the gas film stays thick and non-uniform, resulting in non-uniform thermal discharges (Fig. 4). The electrolyte temperature increases from 42 to 57 °C and the critical voltage decreases from 22.5 V to 22 V as more holes are micromachined from the 9th to 22nd sample the same sequence. In these ranges of electrolyte temperature and critical voltage, the gas film remains thin and uniform, resulting in uniform thermal discharges as shown in Fig. 4. From the 23rd to 38th sample, additional micromachining of holes causes the electrolyte temperature to rise from 57 to 65 °C, resulting in a very thin and irregular gas film that generates irregular & inconsistent thermal discharges.

3.1. I-MR chart of hole depth

The I-MR Chart for the micromachined holes is plotted in this section. The necessary condition for the control charts to be plotted is normally distributed data, which has been checked by using probability plots (Kuo et al., 2017; Tai et al., 2013) in the statistical software, Minitab. Using Ander Darling (AD) method, probability plot (Fig. 5) is used to check the normality of the data. The p value is found to be greater than 0.05, which indicates that data is normally distributed with 95% confidence interval. Therefore, the set of data generated pertaining to microhole is fit to be used for I-MR Chart.

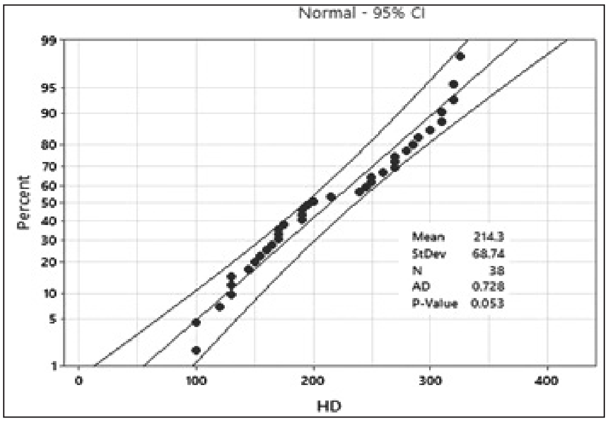

Fig. 5. Probability distribution of the hole depth (HD) data generated from ECDM.

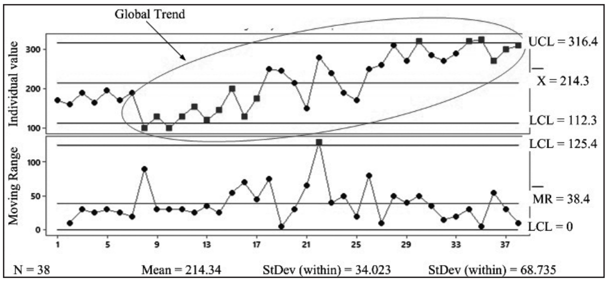

Fig. 6. I-MR chart of hole depth (HD) from ECDM process.

In Fig. 6, MR chart show that majority of the points are falling with in the control limits, which is an indication of consistency in data taken and consequently, the control limits calculated based upon these values are considered reliable for I-Chart. In I-chart, for a controlled and stable process threshold is 0.7% i.e., maximum 0.7% points can fall out of control limits. In the present study of I-chart, it can be observed that around 42.1% points are falling out of the control limit with an increasing global trend. These combined effects indicate that the process is uncontrolled and unstable. Which is attributed to the inherent variation in the process due to increase of electrolyte temperature and variation in electrolyte concentration (due to thermal diffusion and gravitational effect) during machining. Consequently, this process requires improvement in a such a way that electrolyte temperature is controlled, and uniform concentration of electrolyte is maintained throughout the machining.

4. Compositional Analysis of Machined Microholes

High temperature simultaneously accelerates the substrate's chemical etch rate, which is one of mode of material removal in ECDM (Fascio et al., 2003). The more mobile the metal ions are in the electrolyte, the faster the substance is removed. When using sodium hydroxide (NaOH) to etch glass, hydroxyl (OH) and sodium (Na+) ions diffused into the silicon oxide glass linkages, causing chemical etching to remove the material. Literature reported that chemically etched surface will have less concentration of alkali metals in comparison with original glass (Kolhekar & Sundaram, 2018) and, the etching effect gets accelerated with electrolyte temperature (Jalali et al., 2009). The chemical compositions of the machined microhole's bottom are shown in Fig. 7, which indicate the reduction in Na concentration (i.e., the increasing effect of

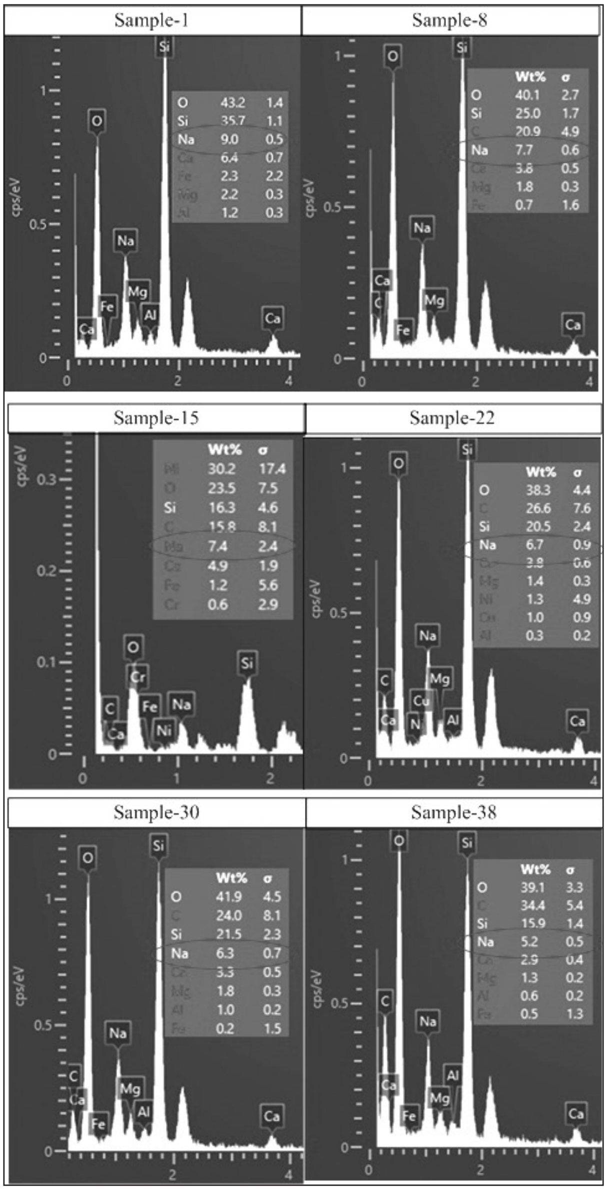

Fig. 7. Chemical compositions of the machined microholes.

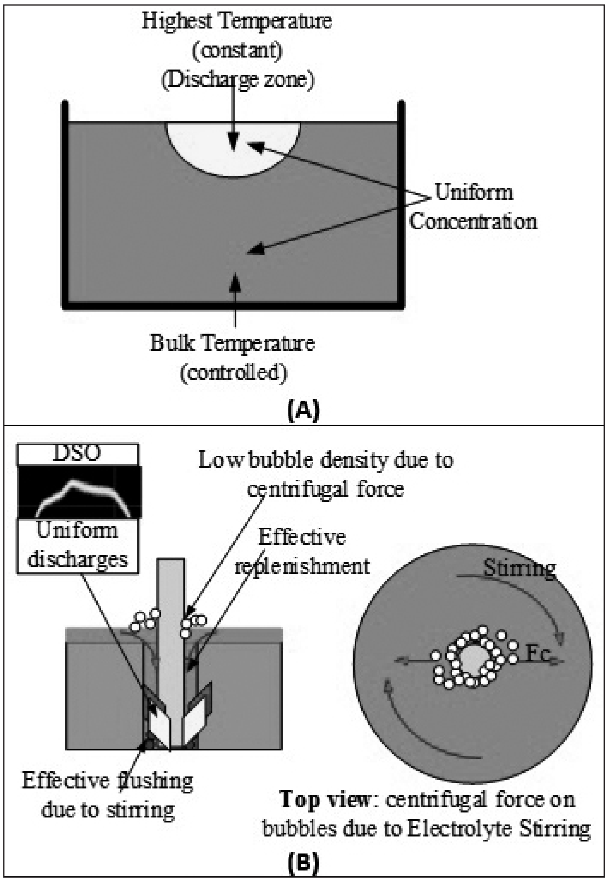

Fig. 8. Process mechanism of the proposed improvements in ECDM.

etching) with machining time. Which is one of the reasons for the increasing trend of hole depth i.e., unstable performance.

5. Conclusions and Future Work

This study has meticulously carried out the stability study on ECDM process using I-MR Chart with probability plot, output from the control chart indicated the instability in the ECDM process. The probable causes are as follows:

- The accumulation of hydrogen bubbles & accumulation of sludge/debris in the machining zone.
- Continuous rise in electrolyte temperature during machining.
- The existence of thermal gradient in the electrolyte bath and electrolyte concentration variation due to thermal gradient.

To stabilize the ECDM process (by tackling the above-mentioned problems) following recommendations are suggested for future work.

- Control the electrolyte temperature at elevated level
- Induce electrolyte stirring

By controlling the electrolyte at a constant temperature and by maintaining homogeneous electrolyte concentration (by virtue of electrolyte stirring) as shown in Fig. 8A, the characteristics of gas film thickness and the characteristics of discharge behavior will remain uniform that will result into the stable performance of the ECDM with respect to machining time. Moreover, stirring action will drift away the accumulated bubbles and elevated electrolyte temperature will result into low viscosity (Vitola et al., 2020), which will enhance the penetration capability i.e., electrolyte replenishment in the machining zone and eventually, stirring action will flush out the debris and sludge from the machining zone (Fig. 8B) that enhance the energy channelization. Eventually, stability of the process will be maintained with respect to the machining depth. To control the temperature and to induce the stirring action in the electrolyte, a magnetic stirrer can be incorporated into ECDM as shown in Fig. 1. Such process can be termed as Temperature cum Stirring assisted-ECDM or controlled-ECDM.

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