ELECTRO CHEMICAL DISCHARGE MACHINING: PROCESS CAPABILITIES

SANJAY K. CHAK
Associate Professor, Manufacturing Processes and Automation Engineering Department
Netaji Subhas Institute of Technology, New Delhi
E-mail: sanjaychak@yahoo.com

Abstract— Electro Chemical Discharge Machining (ECDM) process has combined characteristic of ECM and EDM that enables to machine electrically conductive materials at a rate five to fifty times higher than ECM & EDM irrespective of the typical properties of newer materials such as chemical inertness and high strength high temperature resistance (HSHTTR) by electro chemical dissolution (ECD) and by electric discharge erosion (EDE) simultaneously. The novelty of this process is that electrically non conductive HSHTR materials that are difficult to machine by conventional methods can also be machined by this process. Though this process itself imposes certain limitations such as low machining efficiency, heat affected zone, radial overcut etc. especially while machining some of the electrically non conductive materials but on the other hand this process has been successfully utilized with different conventional machining processes and named as hybrid machining. This paper explains the insight of the mechanism evolved while machining electrically conductive and non conductive materials and focused on the process capabilities of ECDM that has been explored by many researchers and proposed its usage in various forms.

Keywords— Electro-Chemical Discharge Machining (ECDM), High Strength High Temperature Resistant Materials (HSHTTR), Electro Chemical Dissolution (ECD), Electric Discharge Erosion (EDE), Hybrid Machining Processes (HMP).

I. INTRODUCTION

ECM is considered as one of the most versatile method of producing stress free machining on various kinds of metal and alloys. ECM occurs at high current density (greater than 200 amps / cm²) causing rapid dissolution of the anode, and characterized by high surface integrity, improved surface finish, high machining rate and the absence of tool (cathode) wear. But as compared with EDM, it has low accuracy of reproducing the shape of the tool electrode into the workpiece. On the other hand EDM can provide a high surface finish only with a low productivity and an increase in machining rate results in a significantly increased roughness and deeper damaged surface layer, while a reduction in surface roughness leads to increased tool wear. In order to make use of the mutually enhanced advantages of both the processes for gaining high machining rate and improved dimensional accuracy, a hybrid process is in use which is known as electrochemical arc machining (ECAM). This process involves electric discharge erosion (EDE) and electrochemical dissolution (ECD). In ECAM, electric discharge in electrolyte occurs due to electrical breakdown of the vapour-gas layer which causes large number of craters on the workpiece surface, simultaneously these surface irregularities (roughness caused by craters) are reduced by electrochemical dissolution. Hence high material removal rate compared to ECM / EDM and better quality of the surface finish is obtained. This process has potential to machine electrically conductive materials at a rate, five to fifty times higher than ECM & EDM [1] with better dimensional accuracy and good surface finish (provided that the parameters are properly selected), and has been well accepted by the industries to machine HSHTR alloys. Due to high machining efficiency of this process, continual research is being carried out to incorporate better control of the system by adaptive fuzzy logic [2, 3], by intelligent gap width controller [4], by intelligent pulse classification system [5], by computer based real time process monitoring system [6, 7] etc. This process has been effectively used for hole drilling, die sinking and cutting heat resistance alloys, those having tensile strength more than 1500 N/mm² with machining capacity of the order 10⁴ mm²/min, accuracy of 0.04-0.2 mm and surface roughness of Ra = 1.25-2.5 µm. McGeough [8-12] et al. have contributed a lot to understand the mechanism of ECAM and ECDM.

Unlike ECAM, ECDM is used for machining electrically non conductive HSHTR materials. The workpiece which is kept in the vicinity of electrical discharge that occurs at smaller size tool electrode i.e., cathode-electrolyte interface instantly generates a machined cavity over the workpiece surface depending upon the tool configuration and parametric values of an electrochemical cell, while counter electrode i.e. anode which is much larger in size compared to cathode acts as an auxiliary electrode and is just used to complete the electrical circuit as shown in figure 1.

Fig. 1. Schematic line diagram of ECDM setup
Following are the reactions that take place at cathode and at anode in an electrochemical cell when appropriate potential is reached between the inter-electrode gap.

Reactions at the cathode (Tool)
Plating of metal ions:
M⁺ + e⁻ → M, where M represents any anode material.
Evolution of hydrogen gas:
2H⁺ + 2e⁻ → H₂ ↑ (in acidic solution)
2H₂O + 2e⁻ → 2(OH)⁻ + H₂ ↑ (in alkaline solution)

Reactions at anode (auxiliary electrode)
Dissolution of metal ions:
M → M⁺ + e⁻ (in acidic solution)
Evolution of oxygen gas:
2H₂O → O₂↑ + 4H⁺ + 4e⁻ (in alkaline solution)
4(OH)⁻ → 2H₂O + O₂↑ + 4e⁻ (in alkaline solution)

II. MECHANISM OF DISCHARGE GENERATION

The phenomenon of discharge generation in an electrolytic system could be explained as, “in view of high supply voltage compared to ECM process, hydrogen bubble density increases substantially to constrict the current path at cathode (tool)-electrolyte interface. This constriction causes an increase in the resistance and ohmic heating of electrolyte solution in the local region and hence leads to blanketing of the tool by vapour generation and hydrogen gas bubbles. At a critical value of applied potential, this insulating bubble bridge blows off instantly due to intense heating. Consequently, the current suddenly drops to zero through the circuit and discharge takes place along the locations of the bubble bridge” and the process repeats. To have an overview of these three situations in an electrolytic medium, Ghosh A. [13] showed the range of current density Vs voltage used in ECM, ECAM & ECDM processes with their respective state of applied potential (Figure 2a & 2b).

Mechanism of discharge generation in an electrolyte is a complex phenomenon; confusion often arises over the difference between arc and discharge which influences surface integrity and dimensional accuracy of the machined surface to a great extent. The principle and application of ECDM process for machining electrically conductive materials was first reported by Rudroff [14]. ECD phenomenon was described as a suddenly transient and noisy spark of approximately 1µs - 1ms duration, randomly positioned between the two electrodes, while an arc is a thermionic phenomenon of approximately 0.1s duration and occurs at fixed position between the two electrodes. McGeough [15], analyzed EDE process more precisely as electrochemical spark discharge (ECSD) & electrochemical arc discharge (ECAD). The frequency and distribution of discharge among spark and arc affects the material removal rate and the surface finish. High frequencies lead to a more condensed energy over a short period of time resulting in a small crater volume, i.e. a smooth surface and thin heat affected zone on the machined part.

Crichton and McGeough [16-17] explained that both spark and arc discharges were possible in the electrolyte across localized region of gas and / or electrolyte vapour. The type of discharge may have to be distinguished from the energy of the emitted radio frequencies or by the study of the light emitted. Crichton and McGough [17] performed streak photography to get insight into the various stages of discharge by applying the 85 V pulse for a duration of 200 µs. They concluded that the electrical discharge between cathode tool and electrolyte interface occurred due to: (i) generation of electrolytic gas at the surface of electrodes; (ii) the growth of layers of low ionic concentration near the electrodes and formation of oxide films on the anode surface; and (iii) the local variations in the electrolyte flow pattern caused by flow stagnation and eddy. They also categorized the electrochemical action followed by discharge between the electrodes (i.e. ECAM) into four stages, i.e. (i) high frequency oscillations (160-170 Khz), (ii) high rate ECM at 30 volts and 50 ampere, (iii) low rate ECM due to gas generation and (iv) electric discharge action, as shown in figure 3.
Stage 1 represents un-productive period, which can be eliminated by circuit configuration. Stage 2 & 3 together represent an EDM phase. Stage 4 represents an ECM phase. The durations of these phases respectively increase and decrease with increasing the gap width and vary with electrolyte type, concentration and conductivity. Hence, these phases could be controlled to get the desired effect on the components machined by ECDM as shown in figure 3.

Basak [18] proposed that the electrical discharge in electrolyte occurred due to switching action and not due to dielectric break down of the medium. In view of high supply voltage compared to ECM, hydrogen gas bubbles density increases substantially to constrict the current path at tool-electrolyte interface. This constriction causes an increase in the resistance and ohmic heating of electrolyte solution in the local region and hence leads to blanketing of the tool by vapour generation and hydrogen bubbles. At a critical value of applied potential, this insulting bubble bridge blows off instantly due to intense heating. Consequently, the current suddenly drops to zero through the circuit and discharge takes place along the locations of the bubble bridge. This has been claimed as analogous to switching-off effect of an electrical circuit (Figure 4 (a) & (b)), based on Paschen’s Curve from an electric contact theory.

Jain [19] claimed that the switching-off theory proposed by Basak [18] had certain inconsistencies and proposed “Valve Theory” with several assumptions regarding diameter of the bubble, electric field intensity, frequency of spark, etc. in conjunction with the finite element method to compute material removal rate. They considered each gas bubble as a valve, which after its breakdown due to high electric field produced discharge in the form of arc. The process was explained by constructing an equivalent circuit and it was concluded that the sparking during ECSM process was the result of arc discharge. Kulkarni [20], proposed that ECD was a discrete phenomenon. The breakdown is similar to the one that occurs in a gas due to a large electric field of the order of 10^7 V/m which gets generated locally. By a time-varying current measurement method it has been observed that when an isolating film of hydrogen gas bubbles cover the cathode tip portion in the electrolyte, a large dynamic resistance is created and the current through the circuit becomes almost zero. A high electric field of the order of 10^7 V/m gets generated across the cathode tip and isolated electrolyte causing an arc discharge within the gas layers covering the tip. The electrons flow towards the workpiece kept near the cathode tip. This flow of electron is seen as a current spike of about 20 A or more for a short duration of few milliseconds. This bombardment of electrons raises the temperature of the workpiece momentarily and then the temperature decreases due to quenching.

It could be observed that due to complexity involved in this process, different theories have been used to explain the ECD phenomenon. Despite this, the mechanism of material removed in electrically conductive materials has been well explained in the literature by different machining methods (i.e., drilling & die sinking) [21-26] while for electrically non conductive materials, thermo-mechanical and chemical action have been considered by many researchers which depend very much on the property of the material being processed. The studies related to mechanism of material removal from electrically conductive and non-conductive materials have been discussed in this section to identify the influential parameters in ECDM while machining electrically non-conductive HSHTR engineering ceramics.

III. MECHANISM OF MATERIAL REMOVAL IN ELECTRICALLY CONDUCTIVE MATERIALS

The experimental investigation of ECAM for drilling hole on mild steel plate with high feed rate i.e. 15 mm/min to 25 mm/min (max. as high as 80 mm/min) was carried out by Kubota [21]. It was suggested that the bulk of metal removal is achieved by a sparking action in an electrolyte, whilst electrochemical action act as finishing operation which depends on the
quality of electrolyte used. In a parametric study, Drake [65] reported that the ferocity of the sparks in ECAM could cause greater metallurgical damage to the workpiece than that normally associated with EDM. The dimensional accuracy achieved by ECAM was poor compared to EDM, the reason being, former process produced sparks / arc of greater intensity than those found usually in EDM to erode metal.

In an extensive study on drilling holes on different alloys (low carbon chrome steel, cobalt alloy, nickel alloy, low alloy steel), De Silva [23] reported similar findings i.e., material removal at the frontal gap was due to electric discharge erosion while at the side gap electro chemical dissolution of the material occurred. The metallurgically damaged layers, caused by the discharge erosion phase, were wholly or partially removed by the electrochemical dissolution phase. Therefore, a right balance of EDE & ECD controls the surface integrity (Figure 5) and produce smooth, damage free surface finish without sacrificing the metal removal rate.

The experimental verification of the above facts were further studied to have better control on the process by investigating the effect of different process parameters such as machining voltage, frequency and amplitude of tool oscillation, electrolyte type and concentration and the relationship between the tool oscillation and the voltage waveform on surface finish and surface integrity of moulds and dies [24-26]. It was reported that machining at 12 -16 volts improved the flatness of the machined surfaces, while above 16 volts showed the evidence of tool wear & undercut on the machined surface, metal removal efficiency increased with increase in frequency of tool oscillation while it decreased with the increase in amplitude of tool oscillation. Under the effect of 20 wt% concentration of NaNO₃ single phase full-wave rectified unsmooth DC (0-60 V., 200 Amps.) showed high surface finish with low metal removal rate while low surface finish with high metal removal rate was observed with smooth DC (0-30 V., 200 Amps.). The phase relationship between the tool vibration and machining voltage was shown to be an influential factor in ECAM. To enhance machining, ignition of the discharge was made to occur just before the voltage reached its maximum value on each cycle, this ensured stable machining in which discharges and high current density ECM occurred simultaneously.

IV. MECHANISM OF MATERIAL REMOVAL IN ELECTRICALLY NON CONDUCTIVE MATERIALS

Mechanism of material removal in electrically non conductive materials such as glass, quartz, composite, ceramics, etc., has been explained with the help of ECDM phenomenon. Similar to ECAM, mixed state of electric discharge (ED) and electro chemical (EC) machining which includes thermo-mechanical (vaporization, melting, erosion, cavitation, pitting, etc.) and chemical (chemical etching, dissolution) action depending upon the nature of material being processed has been proposed.

The phenomenon of electrical discharge in electrolyte was first utilized by Kurafugi and Suda [27] in 1968. Holes upto the depth of 0.31 mm was drilled on glass plate with cell voltage of 34 volts at 15wt% concentration of NaOH electrolyte. However, the mechanism of material removal was not identified but later it was proved as the most suitable process to machine non conductive materials. In an extensive study on machining of glass and other non conductive materials, Cook et al. [28] reported the process to be polarity dependent and electrolyte sensitive. It was observed that machining rate and depth of cut increased with the increase in supply voltage, electrolyte concentration and temperature, but for a given voltage the rate of machining was found to decrease with time (Fig. 6). The possible mechanism of material removal was explained as thermo mechanical, chemical, electric field and due to some other unknown effects. Experiments were conducted with DC pulsed power supply, where pulse in micro second range increased by a factor two and also produced better surface finish compared to smooth DC power supply.

Allesu [29], conducted an extensive experimental study on ECDM process while machining glass and categorized the mechanism of material removal process into three phases:

i) Electrochemical phase, where the current is carried by the electrolyte without any discharge (Figure 7 (a)).

ii) Discharge phase, where the discharge occurs across the vapour / bubble, the surface activity operates because of the adsorbed electrolyte layer on the work surface. The current flows through the adsorbed layer and discharge takes place across the gas bubble (Figure 7 (b)).
iii) Electrochemical phase occurs when the impressed voltage approaches zero (at the end of the pulse), the electrolyte is back into its original state. The hot surface of the glass undergoes quenching leading to thermal cracking or thermal spalling (Figure 7 (c)). This shows that mechanism depends very much on the workpiece material where thermal heating, cavitation and electro chemical action removes the material.

Apart from this, Allesu [30] discussed associated problems like “limiting depth characteristic” in ECDM. It was explained as a result of loss of potential between the tool electrode and bulk electrolyte with the tool penetration in the workpiece, which was caused by the accumulation of gas bubbles, machined debris and electrolyte under confined conditions inside the hole. It was reported that discharge voltage increased with the increase in flow of electrolyte and upward shifting of discharge zone was observed when tool depth inside the electrolyte / workpiece increased. Basak [31], formulated a mathematical model to predict the material removal rate by varying input parameters and explained that, “machining occurs due to the transmission of a fraction of the spark energy to the workpiece, which raises the temperature of the spot quickly to a very high value and melts the work material spontaneously. A part of the molten portion of the workpiece is removed from the region due to the mechanical shock resulting from sudden phase change and the electrical shock due to the discharge. Figure 8 shows the mechanism of material removal in glass by ECDM process which is based on idealized model of discharge (switching-off situation [18]). In addition, the effect of inductance (in external circuit) on material removal rate was studied to improve the efficiency of the process [32].

Based on ECD phenomenon i.e. “evolution of heat due to sparking”, Jain et al. [33] reported that the material removal process in glass-epoxy and Kevlar-epoxy composites involved evaporation, melting, mechanical erosion due to cavitation (rupture of gas bubble on the workpiece surface) and electrochemical reactions. It was reported that material removal rate, tool wear rate and overcut increased with increase in applied voltage and increase in specific conductivity of electrolyte. Specific conductance of NaOH increased up to 15wt% concentration, beyond that it decreased gradually. They reported the need of further investigation into the mechanism of this process. Material removal mechanism while machining ceramics is more difficult to explain, because they disintegrate instead of melting at high temperature.

Fig. 6. Effect of parameters on material removal rate and machined depth while machining glass [28].

Fig. 7. Proposed mechanism of material removal in glass by ECDM process [29].

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Tokura et al. [34] reported that material removal in ceramics could be due to chemical etching and spalling (cavitation) effect. This is greatly influenced by the applied voltage, so it could not be increased beyond a certain value as ceramics show susceptibility towards crack due to thermal shocks at high voltage. With a stationary gravity fed Ni electrode of 0.5 mm diameter as cathode, a small pit formation was noticed under the influence of full wave rectified DC. Results obtained showed that the pit could be formed on ceramics (Al₂O₃ & SiC) while its depth apparently varied with the ceramic material. It was observed that the volume of material removed, size and depth of the pit increased with increase in voltage and electrolyte concentration. 20wt% concentration of NaOH was found to result in maximum material removed. However, the rate of machining was found to be very low while machining ceramics and concluded that deep drilling of fine holes may not be feasible due to occurrence of abrupt spark which increased with the increase in tool depth inside the electrolyte.

Bhattacharya et al. [35], reported that the machining in ceramics took place mainly due to spark discharge action across the gas bubble layers formed on the workpiece surface. Each electrical discharge causes a focussed stream of electrons to move with a very high velocity and acceleration from the cathode (or tool) towards the workpiece and ultimately creates compressive shock waves on the workpiece surfaces. The phenomenon is accomplished within a few microseconds and the temperature of the spot hit by electrons could rise to a very high value. As this temperature reach above the melting point of the workpiece material, it melts and finally evaporates the material. The high pressure of the compressive shock waves creates a blast, causing metallic vapours to form wear products in the shape of metallic globules, leaving craters in the workpiece surface. The material removal from the workpiece surface during electrical spark discharge is proportional to the pulse energy of the spark, which is released as heat during machining. Some researchers have pointed out that the heat generated by the electrical sparking rather than melting of the hard and brittle ceramics may cause the ceramic materials to spall. This phenomenon is known as thermal spalling, where the material removed is due to mechanical failure without melting. A complex temperature gradient is established due to the sudden temperature change in the machining area of the ceramic materials. It creates internal stresses that may be sufficient to overcome the bond strength of the ceramic grains, resulting in mechanical erosion. The proposed gas bubble formation and sparking phenomenon are exhibited in figure 9. They conducted an experimental study on Al₂O₃ to find the effect of applied voltage (70-90 V), electrolyte concentration (i.e., NaOH at 20wt%, 25wt%, 30wt% concentration) and tool tip shape (i.e., flat front – straight side wall / taper side wall, curvature front – taper side wall shown in figure 10) on material removal rate and radial overcut under the effect of pulsed DC. It was observed that material removal rate & radial overcut increased with the increase in applied voltage & the increase in electrolyte concentration.

Machining at high voltage developed micro-crack while at higher concentration, overcut was increased. The effective range of parametric combination for moderately higher machining rate and dimensional accuracy was centered around 80 V applied voltage and 25wt% NaOH electrolyte solution. Similar results were obtained while machining ZrO₂ and Si₃N₄ with NaOH / KOH electrolytes [36-39]. It was observed that applied voltage had more significant effect on MRR, ROC and HAZ than other parameters [40]. Tool tip was also reported as a prominent factor for controlling spark generation in ECDM. Taper side wall-curvature front tool tip causes maximum amount of electrolyte availability in sparking zone which creates maximum number of sparks and thus increases MRR compared to flat front - straight side wall tool tip / flat front – taper side wall tool tip where the availability of electrolyte in the gap between tool and job is very less as they are always in contact with each other due to the gravity feed force and thus causing occurrence of lower number of sparks.

Moreover, the mechanism of material removal in the ECDM process is very complex in nature and is governed by various process parameters that are still not very clear to researchers. In order to achieve effective and controlled machining, researchers have reported various predominant input parameters while...
machining low temperature materials such as glass, quartz, composites etc. using different machining techniques like drilling, grooving, cutting / slicing etc. On the other hand machining of ceramics is more difficult because they do not have melting characteristic and pose high hardness, high brittleness, chemical inertness at elevated temperature and also susceptible towards crack at high voltage.

Wire electrochemical discharge machining of glass and ceramics was first reported by Tsuchiya [41]. Similar to the concept of wire EDM, wire ECDM was used to study the effect of polarity of electrodes, duty factor, supply voltage, electrolyte concentration and electrolyte flow rate on cutting rate and overcut was examined. It was observed that negative polarity of wire gave higher cutting rate than positive polarity. Cutting rate increased with the increase in voltage and electrolyte concentration. At high voltage & electrolyte concentration, MRR increases but wire melts frequently at high voltage & low concentration and the micro cracks appeared over the machined surface. Cutting rate also increased with increase in duty factor and it became larger with low pulse rate. Glass (soda-lime, silica and borosilicate) and ceramic (Al₂O₃, Si₃N₄ and SiC) plates of 1.2 mm thickness were cut in the range of 2.5 mm / min to 4.0 mm / min and 0.12 mm / min to 0.14 mm / min respectively. Similar findings were reported by Jain et al. [42] while machining piezoelectric ceramic material (i.e. lead zirconate titanate) of 2-3 mm thickness. MRR was found maximum at 22.5wt% concentration of NaOH and average diametric overcut was reported as 0.67mm with 0.5 mm diameter of wire.

In order to increase the volume of material removed and machined depth in ceramics, researchers have tried different machining possibilities such as step drilling [43], vibrating tool [44], gas filled ECDM with side insulated tool [45], introducing external inductor into the circuit for constant supply of power input [46], SiC / graphite powder mixed electrolyte [47-48], rotary and trepanning action of copper electrode [49], etc. and were able to show some improvement. It was observed that rotary motion of electrode gave better results than stationary electrode. This electrode configuration was further modified to machine larger size holes on Al₂O₃ & Quartz [50] by the orbital motion (trepanning) of the tool with comparatively smaller size electrode.

Jain et al. [51] used abrasive electrode with rotary motion under smooth DC voltage to drill holes on Al₂O₃. Results showed that the volume of material removed and depth of cut increased with the increase in supply voltage and electrolyte temperature. But the volume of material removed could not exceed 20 mg at 70 volts and the material showed tendency to cracking beyond these operating conditions. However, these limitations were partially relaxed by introducing pulsed DC power supply with an abrasive electrode that has reduced the tendency of cracking at high voltage and has reduced the taper on vertical surface while drilling deep holes in ceramics. Results obtained indicate that volume of material removed from the workpiece increases with increase in supply voltage, duty factor and electrolyte conductivity. The pulsating nature of current has reduced the could have helped in eroding the work material by intermittent focusing of thermal shocks while the use of an abrasive electrode simultaneously removed the recast layer at the local region and provides additional electrical discharge beneath the tool electrode which improves the machining conditions [52].

Apart from these findings, researcher also tried to develop mathematical models (based on different assumptions) to estimate the critical voltage & critical current using different electrolytes [53], temperature measurement at different radii of the workpiece [54] and electrolytic concentration & energy partition over material removal rate by finite element method [55]. It was observed that with the increase in electrolyte concentration from 10% to 30%, and with the increase in energy partition, material removal rate increased significantly especially in soda lime glass while machining Al₂O₃, similar trend had been observed with low variation in results due to its high hardness at elevated temperature.

On the other end, this process has also shown the different possibilities to machine electrically non-conductive HSHTR materials when the configuration of electrodes is modified. Though comparatively low machining efficiency was obtained, but researchers have made successful use of this process to machine such materials by different techniques like, 3D micro structuring of glass (Fig. 11) [56-60], slicing (cutting) of glass / quartz / glass & kevlar fibre epoxy composites (Fig. 12) [61-64], drilling of composites / glass / quartz (Fig. 13) [64-71], chemical engraving of glass (Fig. 14) [72-76] etc. Apart from machining / truing & dressing of metal bonded diamond grinding tools by centerless grinding (Fig. 15) [77-79], micro welding (Fig. 16) [80] and ECD fused deposition for rapid prototyping (Fig. 17) [81, 82] are the variants of ECDM that is used for developing precision 3D micro structures layer by layer similar to additive manufacturing, but they are less discussed in the literature.

Fig. 11. 3D micro structuring of glass: (1) tool electrode with the holder mounted on a voice coil motor, (2) anode (3) glass sample,(4) electrolyte (5) XYZ stage [56].
V. HYBRID MACHINING PROCESSES

Compared to electrically conductive materials, machining of HSHTR engineering ceramics is more difficult because they pose high hardness and brittleness at high temperature. Despite their outstanding characteristics, applications of these ceramics is limited to only specialized fields due to inherent machining problems such as, low material removal rate, high tool wear rate, possible damage to the workpiece, high surface roughness and poor dimensional accuracy. Due to these reasons, efficient processes like electrochemical machining (ECM) and electric discharge machining (EDM) are not suitable to machine these ceramics, while other non-traditional / hybrid machining processes need thorough investigation on important aspects like surface integrity, dimensional accuracy, heat-affected zone, etc. of the machined surface.

The recent trend of combining different physiochemical action on the material being removed has shown improvement in machining. In particular a mechanical action, which is used in conventional material removal processes can be combined with respective interactions applied in unconventional manufacturing processes to make use of the combined or mutually enhanced advantages, and to reduce some adverse effects the constituent processes produce when they are individually applied. This trend of hybrid machining process (HMP) has now been extended to develop the processes like abrasive electric discharge grinding (AEDG), abrasive electrochemical grinding (AECG), abrasive electric discharge machining (AEDM) / powder mixed electric discharge machining (PMEDM), ultrasonic assisted electrical discharge machining (USEDM), ultrasonic assisted electro chemical machining (USECM), electro chemical discharge machining (ECDM), abrasive electro chemical discharge machining (AECDM), powder mixed electro chemical discharge machining (PMECDM), etc. for improved productivity / diversified applications, as shown in the figure18.
Abrasive assisted electrical machining methods are becoming popular, as it facilitates additional cutting action, removal of recast layer / oxide film and improved surface finish during machining. This technique is now being effectively used by many researchers to machine electrically conductive & non conductive HSHTR materials such as carbide / magnetic alloy / steel / titanium alloy / metal matrix composite / Al-SiC / cemented carbide by AEDG [83-85], sintered carbides / creep resisting alloys / titanium alloys / metallic matrix composites (e.g. PCD-Co, Al-SiC, Al-Al2O3) by AECG [86, 87], ferrous alloys by PMEDM [88, 89] and by AECF [90].

Among these methods, abrasives assisted ECDM process is gaining more popularity especially in micro machining of electrically non conductive materials, because it involves combined action of electrical discharge, chemical etching and abrasive cutting. Yang et al. [47] claims that loose abrasives particles disrupt the bubble accumulation to form an isolating layer around the tool electrode in ECDM. As a result, the measured critical voltage is higher in the electrolyte with abrasives than in the pure electrolyte. More energy is wasted in the bubble isolation layer and less energy is released during the removal of material by discharge heating, thus it reduces the overcut. It is observed that diametric overcut and surface roughness increased with increase in grit size. Material removal rate also increased with increase in abrasive concentration but saturates beyond 100gm/L. Smaller abrasive grit size improves the dimensional accuracy and surface finish of the product. Higher power frequency with smaller size abrasives also helps to refine / remove the microcracks and the melted zone formed by the discharge heat. The lapping force exerted by the relative motion between the abrasives and the workpiece promotes surface finish. Thus quality of slit produced on Pyrex glass by wire ECDM can be well controlled (KOH with 300g/L SiC, #200, 100Hz, Duty factor 0.25).

Min et al. [48] claims that the use of fine abrasive graphite powder in ECDM helps to improve the surface integrity of the machined surface. By the use of 1.0 wt% graphite powder concentration in 30% NaOH, the number of microcracks was significantly reduced and the surface roughness was improved from 4.86 to 1.44 µm. Graphite powder possesses good thermal and electrical conductivity therefore it intensifying the local electric field that reduces the spark initiation voltage [91]. The dielectric strength of hydrogen film depends on the condition of conductive particle such as number, size, chain shape of the particles [92]. When a particle is subjected to an electric force, it tends to detach itself from the electrode [93]. This charged particle attached to or moves between the electrodes, the potential between the electrodes decreases [94]. A micro discharge is caused if the detached particle approaches to the opposite electrode and likewise successive micro discharges in the hydrogen film results in the electrical breakdown [95].

CONCLUSION

This study reveals that much has been discussed about the electrochemical discharge phenomenon and its application while machining electrically conductive and electrically non conductive materials. Since material removal in ECAM has been well explained, continuous improvement for its development is in progress and it is being effectively used to machine electrically conductive HSHTR materials with higher material removal rate and improved dimensional accuracy than ECM & EDM. This discharge phenomenon has also been used to machine electrically non conductive materials and the process was named as ECDM. It was observed that ECDM had low machining efficiency due to inherent machining problems, therefore materials like glass, quartz, composites etc. those having ability to melt (at discharge temperature) were machined by this process. Researchers have also reported that ECDM could be a viable solution for machining electrically non conductive HSHTR ceramics, but realizing low efficiency of the process hybrid machining especially involving abrasives or electrically conductive powder mixed electro chemical discharge machining may further improve the machining performance. This process could be used for diversified applications such as 3D micro structuring, electro chemical discharge based fused deposition for rapid prototyping, slicing / grooving of glass / quartz /
composites, trueing / dressing / centerless grinding of metal bonded diamond grinding tools, micro welding etc.

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