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Electrochemical Discharge Machining - Discharge Generation: A Review

Sanjay K. Chak

Manufacturing Process and Automation Engineering Department
Netaji Subhas Institute of Technology, New Delhi-110078
E-mail: skchak@yahoo.com

Abstract—*Advanced engineering materials which are widely used as high strength refractory material for several industrial applications, always pose a challenging opportunity to machine them. Conventional methods of machining are difficult to shape them because of their high hardness and brittleness, An hybrid machining process (HMP) has now being developed which combines the characteristics of electrochemical machining (ECM) and electric discharge machining (EDM), has shown potential to machine electrically non conductive, High-Strength-High-Temperature-Resistant (HSHTR) materials like ceramics, quartz, glass, composites, etc. is known as Electro-Chemical Discharge Machining (ECDM) Process. Though this process has been successfully applied to machine different materials, but the associated problems during machining such as, radial over-cut, low material removal rate, poor dimensional accuracy, etc., are required to be optimized. The aim of this paper is to provide a report on the study conducted by various researchers specifically on the mechanism of material removal in different materials and the discharge generation in ECDM to overcome these problems.*

Keywords*: Hybrid Machining Processes (HMP), Electro-Chemical Discharge Machining (ECDM), High Strength High Temperature Resistant Materials (HSHTR), Discharge Generation.*

1. INTRODUCTION

Materials used in nuclear research, aerospace and electronic industries like high chrome steel, nickel and titanium alloys, piezoelectric ceramics, carbon fiber epoxy composites, kevlar / glass fiber epoxy composites, silicon nitride, aluminum & zirconium oxide, quartz, borosilicate glass, etc., possess typical inert properties and comes under the category of high strength high temperature resistant (HSHTR) materials. To machine such materials, by conventional methods, has become very difficult and uneconomical. However, few unconventional machining processes, like AJM, USM, EBM & LBM, can machine these materials, but some of the important aspects like surface finish, surface integrity, dimensional accuracy, heat affected zone, etc., of the machined surface are yet to be investigated. To overcome this challenging problem, researchers [1, 2] have found a novel method of machining, by combining the characteristics of ECM & EDM. This process is called Electro-Chemical Discharge Machining (ECDM). It has potential to machine electrically conductive materials at a rate, five to fifty times higher than ECM & EDM [3, 4] and is also popular to machine electrically non-conductive, HSHTR materials.

In an electro-chemical cell, if one electrode is very small and other is relatively much larger in size, the current distribution will be non- uniform, which results in electrical discharge at the interface of tip of the smaller electrode and electrolyte. If the supply voltage exceeds a critical value, material removal takes place and this process is known as ECDM (Fig. 1). The common electrolytes used in this process are NaOH, $NaNO_3$, NaCL, and KOH. This process has wide variety of industrial applications such as engraving, drilling, cutting (slicing), micro welding, dressing of metal bonded grinding wheels, etc.

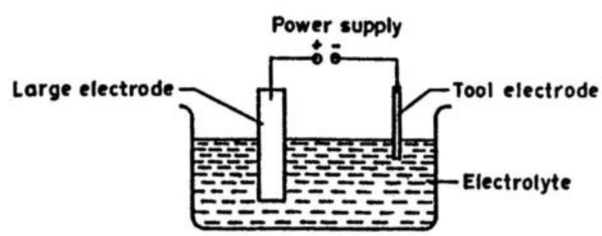

Fig. 1: Electro-Chemical Discharge cell

The important machining parameters of ECDM process are material removal rate, depth of machining, radial over-cut, surface finish and dimensional accuracy of the machined profile. These are influenced by applied voltage, electrolyte concentration, area of tool cross-section dipped inside the electrolyte and inter-electrode gap. Hence the effect of these parameters on the process needs to be studied.

From the previous studies, it has been observed that the machining rate increases with applied voltage, concentration and temperature of the electrolyte up to certain limit and then decreases [5-9]. This process needs to be thoroughly understood in order to achieve precision in machining such as drilling of deep fine holes with minimum over-cut, controlled dimensional accuracy of the machined surface with minimum heat affected zone, improved material removal rate, etc. and still requires further investigation. Though researchers have used different techniques to overcome these problems, few of them have been identified for better control of the process. This can be achieved by modifying the power supply to D.C. pulse (micro-sec. pulses) supply to improve the machining rate and surface finish [3-5, 10, 11], by introducing an external inductor into the circuit for constant supply of power input [12], by making an electrically non-conductive gas between (cathode) tool electrode-electrolyte interface control the discharge generation in a better way [13] and by insulating the tool to reduce the radial over-cut [13]. But in order to enhance the overall machining performance of the process, proper understanding of the mechanism of material removal, specifically in electrically non-conductive materials like ceramics, is essential in addition to the comprehensive study on the discharge generation and this paper provides insight into this.

2. MATERIAL REMOVAL MECHANISM

In order to understand the issues related to the discharge generation, thorough understanding of the mechanism of metal removal is required. Work materials could be broadly classified into two groups to analyze the material removal mechanism in different materials: electrically conductive materials and electrically non-conductive materials.

The process of material removal in electrically conductive materials is known as Electro Chemical Arc Machining (ECAM) [3, 14]. This process involves electrochemical dissolution (ECD) and electric discharge erosion (EDE). Due to maximum contribution towards metal removal, EDE process has been analyzed more precisely as electrochemical spark discharge (ECSD) & electrochemical arc discharge (ECAD) [3, 11, 14]. The frequency and distribution of discharge among spark and arc also 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 [3].

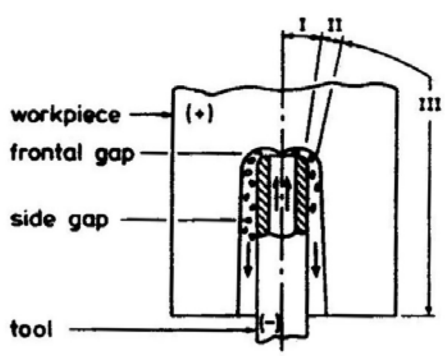

Fig. 2: Electro-Chemical Arc Drilling

De Silva [14] attempted the drilling on metals by ECAM process and proposed that material removal at the frontal gap is due to electric discharge erosion while at the side gap electro chemical dissolution of the material occurs. The metallurgically damaged layers, caused by the discharge erosion phase, are wholly or partially removed by the electrochemical dissolution phase. Therefore the proportion of ECD & EDE controls the surface integrity (Fig. 2).

(I) almost EDE, (II) combined ECD and EDE and (III) almost ECD [14].

The process of material removal in electrically non-conductive materials is known as Electro Chemical Discharge Machining. The work material is placed in the vicinity of the discharge, this local discharge generation causes high temperature and pressure, which gives rise to material removal. This could be due to vaporization, melting, erosion, cavitation, pitting, dissolution, chemical etching etc.. All of these depend on the properties of work material, type of electrolyte and machining parameters. So, the analysis should be on the basis of above mentioned parameters.

Material removal mechanism for machining of ceramics is more difficult to explain, because they are very hard, brittle, and more susceptible towards crack at high temperature and possess low thermal conductivity. Material removal 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. So, deep drilling of fine holes may not be feasible as the possibility of occurrence of abrupt spark is greater at a greater tool depth inside the electrolyte [15, 16]. This makes tapered surfaces as shown in Fig. 3.

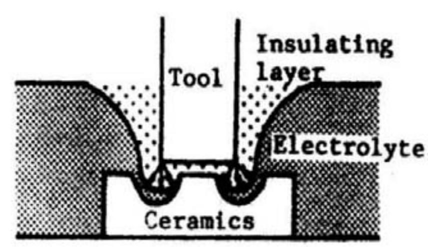

Fig. 3: A material removal model of ceramics by ECDM process [15]

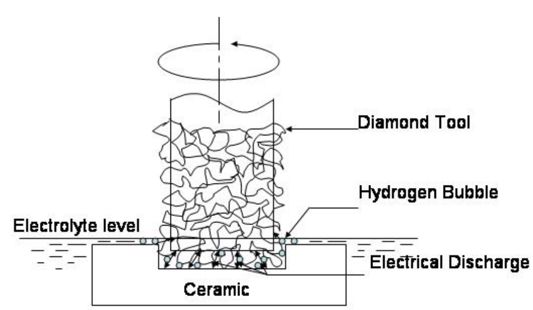

Fig. 4 Schematic line diagram of ECDM using spring fed cylindrical rotary abrasive electrode [17]

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 as shown in Figure. 4. The pulsating nature of current 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 [17].

Jain V.K. [18] reported that the material removal process in glass-epoxy and Kevlar-epoxy composites involves evaporation, melting, mechanical erosion due to cavitation and electrochemical reactions. Allesu K., [7] categorized the mechanism of material removal in machining of glass, into three phases:

i) Electrochemical phase, where the current is carried by the electrolyte without any discharge (Fig. 5(a)).

ii) Discharge phase, where the discharge occurs across the vapor/bubble, the surface activity operates because of the adsorbed electrolyte layer on the work surface. The current flow through the adsorbed layer and discharge takes place across the gas bubbles (Fig. 5(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 (Fig. 5(c)). This shows that mechanism depends very much on the workpiece material.

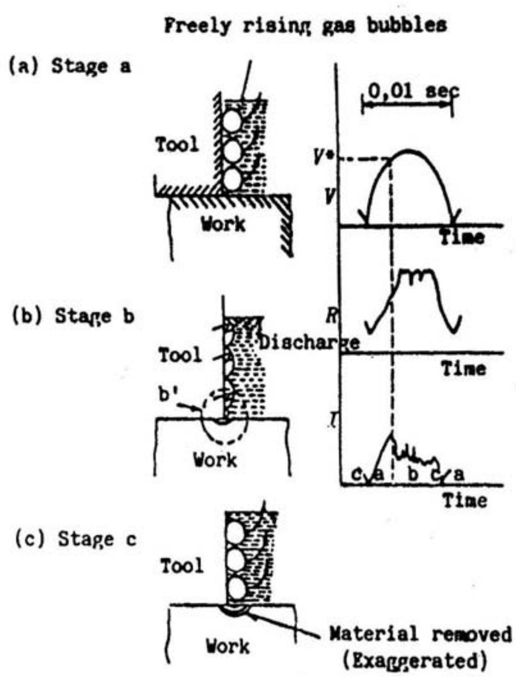

Fig. 5: Proposed mechanism of material removal in glass [7].

3. MECHANISM OF DISCHARGE GENERATION

It is evident from the above studies that the nature of the discharge influences the surface integrity and dimensional accuracy to a great extent and hence thorough understanding of the mechanism of discharge generation is essential.

Basak I. [19] proposed that in ECDM, in view of high supply voltage compared to ECM, hydrogen bubble 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 vapor generation and hydrogen 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. This has been claimed as analogous to switching-off effect of an electrical circuit (Fig. 6 (a) & (b)).

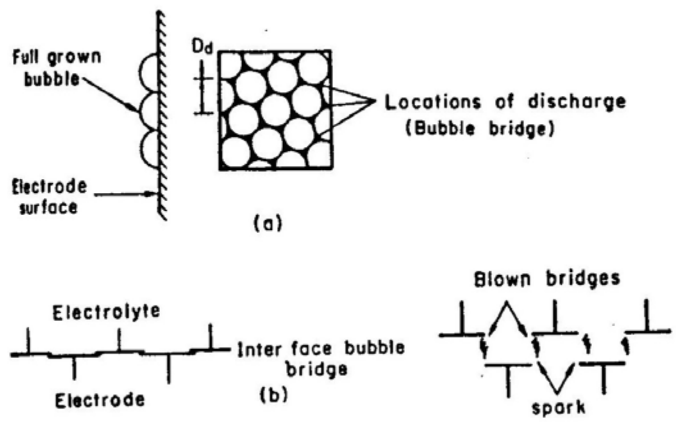

Fig. 6: (a) Discharge locations with bubble distribution at critical condition. (b) Idealized switching-off situation [19].

Jain V.K. [20] claimed that switching-off theory proposed by Indrajit Basak [19] has certain inconsistencies and proposed "Valve Theory" in conjugation with the finite element method to compute material removal rate. 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.

Since the mechanism of discharge generation in an electrolyte is a complex phenomenon, confusion often arises over the difference between arc and spark (discharge). This has received little attention by the researchers and still in research stage. Rudrof [1], describes the discharge phenomenon as a sudden 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, occurs at fixed position between the two electrodes. Crichton and McGeough [4], concluded that electrical discharges in an electrolyte occur across localized region of gas and/or electrolyte vapor, both spark and arc discharges are possible in an electrolyte. The type of discharge may be distinguished from the energy of the emitted radio frequencies or by the study of the light emitted. McGeough categorized the electrochemical action followed by discharge between the electrodes (i.e. ECAM) into four stages, (i) high frequency oscillations (160-170 KH_Z), (ii) high rate ECM at 30 volts and 50 ampere, (iii) low rate ECM due to gas generation and (iv) electric discharge action (Fig. 7).

Stage 1 represents un-productive period, which can be eliminated by circuit configuration. Stage 2 & 3 together represent an ECM phase. Stage 4 represents an EDM phase. The durations of these phases respectively increase and decrease with increasing 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 this process involves large number of factors, it requires mathematical modelling to optimize the process.

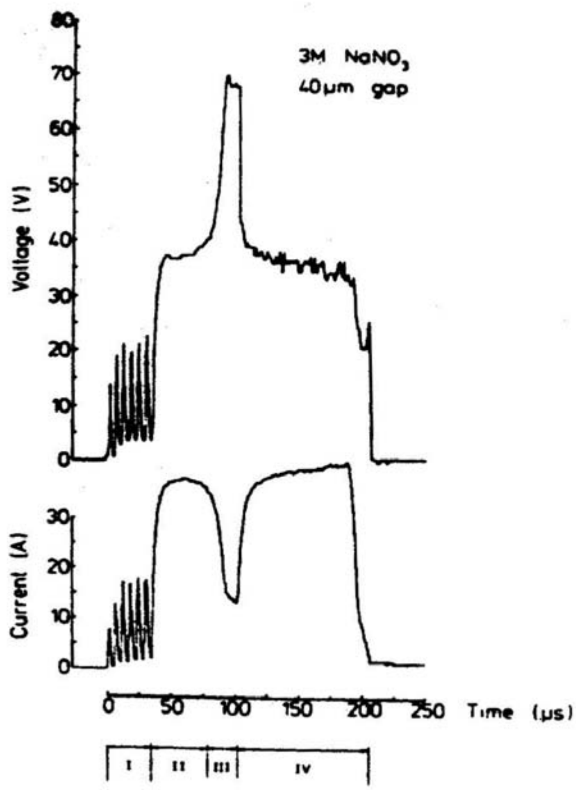

Fig. 7: Electrical phenomenon during ECAM with a square wave pulse [4].

From the available literature, it has been observed that the mechanism of electrochemical discharge is a complex phenomenon comprising of different state of electrochemical reactions. However, it has been established that the discharge takes place due to electrical breakdown across the hydrogen gas bubbles generated due to the electrochemical reaction.

4. MATHEMATICAL MODELLING

Electrochemical discharge machining process is a complex phenomenon and a full mathematical model of this process is difficult. In addition to this, as the mechanism of material removal rate is not properly understood as yet, it would be further difficult to model this process. However, researchers attempted to model certain aspects of ECDM process.

McGeough [3] formulated an approximate value of metal removal rate in ECAM, by developing a model of ECM as a component of ECAM. The theoretical value of metal removal rate in ECM was calculated and compared with the experimental value of metal removal rate in ECAM. The difference between two values of metal removal rate may be attributed to the discharge component in ECAM. It is difficult to give the actual occurrence of ECM and EDM phase in ECAM, the proportion between two must be balanced to achieve a desirable machining rate. McGeough [21] found that the probability of occurrence of ECM and EDM phase simultaneously in ECAM was very less.

Basak I. [19] proposed a theoretical model on ECDM, based on an ideal mechanism leading to switching-off effect, which provides reasonably good estimate of conditions occurring at the on set of discharge. He suggested empirical formulae to predict the critical voltage and critical current to initiate discharge, with smooth D.C. power supply.

Doloi B. [22] applied Taguchi method to optimize the parametric condition of ECDM. In order to obtain optimal machining performance, optimization for higher value of signal /noise ratio was carried out, which provide the maximum value of material removal rate and minimum value of radial over-cut. Thorough analysis of these models and the development of few other models are required for further understanding of the process.

Chak S.K.[23] proposed a regression model based on second order response surface to generate the intermediate data of volume of material removed on the basis of combined effect of input parameters used in central composite rotatable design (CRRD).

5. CONCLUSION

This study underlined the importance of understanding the mechanism of discharge generation. One important aspect of the findings of this paper is that the mechanism depends very much on the workpiece material. Parameters such as pulse duration, pulse width could also change the mechanism of material removal and hence affect the component characteristics. So, the research studies should be goal oriented to identify the optimum parameters for achieving the good surface integrity and dimensional accuracy.

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