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Research Article

MODELING AND SIMULATION OF THERMAL DAMAGE ON GLASS WHILE MACHINING THROUGH ECDM

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ABSTRACT

Industrial applications of glass and ceramic materials have increased manifold due to their relatively low friction, high compression strength, high temperature and wear resistance, and excellent chemical inertness, etc. In micro-electromechanical systems (MEMS) the use of glass, along with silicon and polymer, has become very popular. However, micro-fabrication of glass is a difficult process. The electrochemical discharge machining (ECDM) is now often used as one of the chip less machining solutions for these materials. The ECDM, however, is a complex process with multiple controllable parameters and exhibits stochastic nature. The mechanism of material removal in the process is yet to be understood well in spite of many theories. In this thesis, an attempt has been made to model and simulate thermal damage while machining through Electro chemical discharge machining (ECDM).

INTRODUCTION

In his quest for knowledge, man is exploring the universe. This call for state-of-the-art technologies to attain the maximum speed, sense the weakest signal, actuate in the shortest time possible, etc. Thus, the quest for knowledge touches upon all the branches of science and engineering. Machining is the most basic need in engineering. New methodologies and processes need to be invented and researched continuously. Recent trends in product miniaturization have grown in automotive technology, space technology, information technology, bio-technology, environmental and medical applications, etc. Micromachining and Nano-machining have become the necessity to meet the intriguing challenges of product miniaturization. Since the very beginning of history, and even prehistory, humanity has invested a lot of effort in developing the skill of processing materials. There is no need to present the fundamental importance of the capability of machining in any technology. Any new technology requires new machining skills. In the last century, the need for using more and more specialized materials (e.g., silicon, composites, or ceramics) greatly increased the already large arsenal of machining technologies. The last century also saw the birth of micromachining, in particular micromachining of silicon.

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At present, a huge variety of micro machining techniques are available for silicon. A similar situation exists for electrically conductive materials, where, in particular, electrochemical machining (ECM) and electrical discharge machining (EDM) are two very powerful tools available. However, several electrically non-conductive materials are also of great interest for many applications. Glass and composite materials are two examples. The technical requirements for using glass in micro systems are growing. Medical devices requiring biocompatible materials are only one of many examples. The importance of glass is also growing in the field of micro-electromechanical systems (MEMS). The term MEMS refers to a collection of micro-sensors and actuators. MEMS emerged in the 1990s with the development of processes for the fabrication of integrated circuits. In particular, Pyrex glass is widely used because it can be bonded by anodic bonding (also called field-assisted thermal bonding or electrostatic bonding) to silicon. Glass is widely used due to its transparency, low electrical and thermal conductivity. Glass has some very interesting properties such as its chemical resistance or biocompatibility. It is amorphous and can therefore be chemically attacked in all directions. As glass is transparent, it is widely used in optical applications or in applications where optical visualization of a process is needed. Some promising applications for glass in the MEMS field are micro-accelerometers, micro-reactors, micro-pumps, and medical devices (e.g., flow sensors or drug delivery devices).

A representative example in which glass-to-silicon bonding is used are bulk micro-machined accelerometers. In this case, glass serves several functions:-

- provides a seal and the desired damping;
- can be used as a capacitor when a metal plate is placed on it;
- can be an overload protection.

The use of glass is also very common in other sensors than accelerometers using capacitive sensing technology. Micromachining of electrically non-conductive brittle hard glass is very difficult. Diamond grinding can provide good geometrical accuracy and surface finish, but the machining efficiency is extremely low. Chemical etching is well-established, but its large taper angle and low aspect ratio are undesirable. Laser blasting is costly and tends to cause thermal damage on the machined surface. Ultrasonic machining is difficult to maintain good surface integrity. Recently, electrochemical discharge machining (ECDM) has been used for machining non-conductive glass, which has many applications in Micro-Electro-Mechanical systems (MEMS) and microfluidic systems.

ECDM has emerged as a promising technology for micromachining glass. In ECDM, as shown in Figure 1.1, tool electrode (cathode) and auxiliary electrode (anode) are immersed in an electrolyte solution (typically NaOH). Both electrodes are connected to a DC power supply. When the applied voltage is higher than a critical value, bubbles are generated due to electrochemical reactions. When the bubbles become sufficiently dense enough, they coalesce into a gas film on the tool electrode. The gas film allows sparking between the tool electrode and the electrolyte by isolating the tool from the electrolyte. If the work piece is brought, close to the tool, (e.g., 25 µm for glass), material removal will occur. Although the exact material removal mechanism is not well understood, it is believed that both thermal erosion and chemical etching contribute to the material removal.

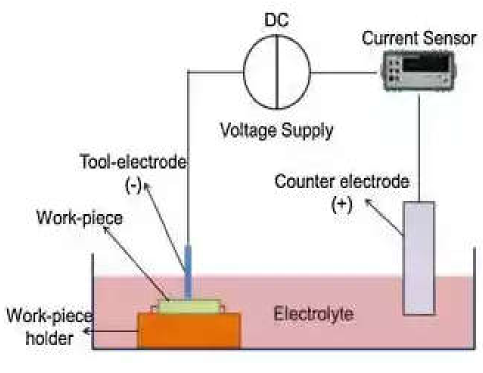


Figure 1. Principle of electrochemical discharge machining

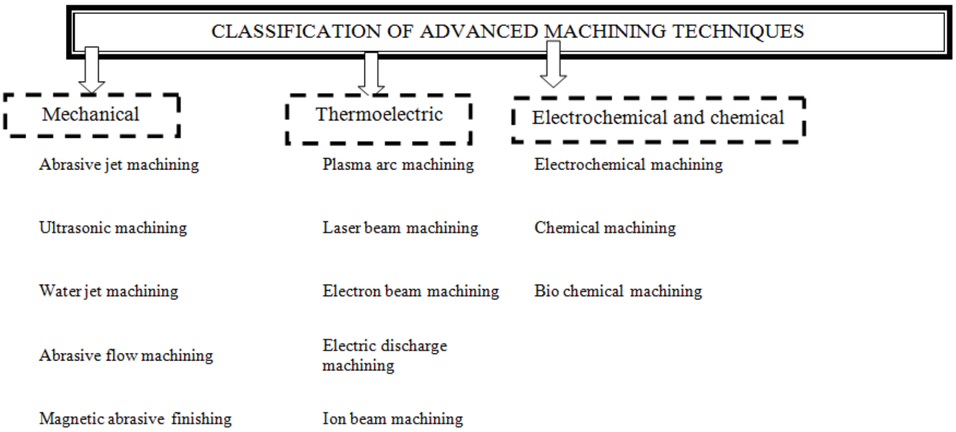
ECDM gravity-feed (constant force between the tool and workpiece) drilling is the most common type of ECDM. Wüthrich *et al*. (2006) characterized the material removal rate (MRR) as a function of drilling depth for micro-hole gravity-feed drilling. Two drilling regimes were identified. During the first 200-250 µm of the hole depth, in the discharge regime, discharge effect dominates and drilling speed depends on the number of discharges.

As the hole is drilled deeper, the drilling speed becomes as low as a few µm/sand nearly independent of applied voltage in the hydrodynamic regime. Maillard *et al*. (2007) characterized the geometry and surface quality of micro-holes drilled in glass. The authors revealed that high machining voltage and high machined depth lead to low geometric quality. Therefore, ECDM deep hole drilling with high geometric accuracy and acceptable machining time is rather challenging. To improve the machining performance of ECDM, various methods have been presented. Tool rotation and tool vibrationare shown to improve geometric accuracy and machining speed in ECDM. Using abrasive tools in ECDM was found to increase machining speed by additional abrasive material removal and the spark gap created by abrasives. Conductive particles and ultrasonic vibration in electrolyte, offset pulsed voltage power and specifically-designed tool geometry were also reported.

The objective of this study is to improve both the material removal rate and machining accuracy of ECDM by using micro-drilling tools. Unlike EDM or ECM, the tool and workpiece can contact in ECDM. Therefore, we expect that using micro-drilling tools can provide additional material removal by generating chips. Rotational micro-drilling tools are used in ECDM instead of traditional cylindrical electrode, which makes it a hybrid process of micro-drilling and ECDM. The machining performances of ECDM drilling with stationary cylindrical tools, with rotational cylindrical tools and with rotational micro-drills are compared. Tool rotation rate, a key parameter for this hybrid process, is experimentally studied. Material removal mechanism of ECDM using micro-drills is investigated using a scanning electron microscope (SEM).

Need for Advanced Machining Process

Technologically advanced industries like aeronautics, nuclear reactors, automobile etc have been demanding materials like high strength temperature resistant (HSTR) alloys having high “strength to weight” ratio. Researches in the area of materials science are developing materials having higher strength, hardness, toughness and other diverse properties. This also needs the development of improved cutting tool materials so that the productivity is not hampered. It is a well-established fact that during conventional machining process an increase in hardness of work material results in a decrease in economic cutting speed. It is no longer possible to find tool materials which are sufficiently hard and strong to cut (at economic cutting speeds) materials like titanium, stainless steel, nimonics and similar other high strength temperature resistant (HSTR) alloys, fiber- reinforced composite, stellites(cobalt based alloys), ceramics and difficult to machine alloys. Production of complex shapes in such material by traditional methods is still more difficult. Other higher level requirement are better finished, low values of tolerances, higher production rates, complex shapes, automated data transmission, miniaturization, etc Making of holes (shallow entry angles, non-circular, micro-sized, large aspect ratio, a large no. of small holes in one work piece, contoured holes, holes without burrs, etc) in difficult-to-machine materials is another area where appropriate processes are very much in demand. Aforesaid characteristics are commonly required in the products used in industries like aerospace, nuclear reactors, missiles, turbines, automobiles, etc.



To meet such demands a different machining processes (i.e. non-traditional machining processes or more correctly named as advance machining processes) have been developed. There is a need for machine tools and process which can accurately and easily machine the most difficult- to-machine materials to intricate and accurate shapes. The machine tools should be easily adaptable for automation as well. In order to meet this challenge, a number of newer material removal processes have now been developed to the level of commercial utilization. These newer methods are called unconventional in the sense that conventional tools are not employed for metal cutting. Instead energy in direct form is used to remove the material from the workpiece. The range of applications of the newly developed machining process is determined by the work material properties like electrical and thermal conductivity, melting temperature, electrochemical equivalent etc. some of these newly developed processes can also machine workpiece in the areas which are inaccessible for conventional machining methods. The use of these processes is becoming increasingly unavoidable and popular at the shop floor.

Process for Advanced Machining

Advanced machining processes can be classified into three basic categories, i.e. mechanical machining processes, thermo electric machining processes and electrochemical and chemical machining processes. None of these processes is the best under all machining situations. Some of them can be used for electrically conductive materials while others can be used for both electrically conductive and electrically non conductive materials. Performance of some of these processes is not very good while machining materials like aluminum having their distinct characteristic features. Hence, selection of an appropriate machining process for a given situation becomes very important.

Hybrid Processes

To further enhance the capabilities of the machining processes, two or more than two machining processes are combined to take advantage of the worthiness of the consistent processes. For example, conventional grinding produces good surface finish and low values of tolerances but the machined parts are associated with burrs, heat affected zone and residual stresses. However, electrochemically machined components do not have such defects. Hence, a hybrid process called electrochemical grinding (ECG) has been developed. In the same way, other hybrid processes like electrochemical spark machining (ECSM), electro chemical discharge machining (ECDM) etc have been developed.

Electro Chemical Discharge Machining (ECDM)

The electrochemical discharge machining (ECDM) process is a combination of electrochemical machining (ECM) and electrical discharge machining (EDM) processes. This process has very good potential in the area of micromachining nonconductive hard and brittle materials such as ceramic, glass, quartz and Pyrex. ECDM process involves melting and chemical etching of the work piece due to high electrical energy discharged on the tip of the electrode during electrolysis. The literature reveals that combined metal removal rate in ECDM can be 5 to 50 times over EDM and ECM with decreased electrode tool wear 2–5. ECDM process requires two electrodes. One is the tool electrode, which is used to produce desired machined shape, and the other is the counter electrode or auxiliary electrode made as anode. The workpiece and counter electrode (anode) are immersed in an electrolyte solution (typically sodium hydroxide or potassium hydroxide). The tool electrode (cathode) is kept 2–3mm dipped in the electrolyte.

Counter electrode or anode is a large size dummy electrode in general, which is kept at a distance of about 25– 50mm away from the tool electrode. Electrolysis starts when a voltage is supplied by a direct current (DC) power source between the tool electrode and counter electrode. A schematic of the process is shown in Figure 1.1. Surface area of the tool electrode submerged in the electrolyte is kept very small compared to counter electrode (anode). This results in high current density at the cathode. Rapid production of hydrogen gas bubbles takes place at the cathode due to ohmic heating of the electrolyte solution. Surrounding electrolyte insulatesthe immersed tool electrode (blanketing effect) by a gas film due to bubble coalescence as shown in figure 1.2. Gas film plays a key role in machining during ECDM.

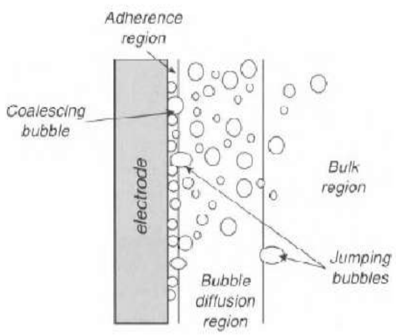


Figure 2. Bubble diffusion region of ECDM process

A stable and dense gas film conditions the machining process. A stable gas film can be achieved by either low terminal voltage with spark generation or periodic formation of the gas film. An unstable gas film results in fluctuating spark and results in non-repeatable machining. Spark action takes place between the tool and the work piece when the current density of the tool exceeds the critical value (typically around 1A) and applied voltage also becomes more than the critical voltage (approximate 25V). The critical value of current and voltage depends on the geometric shape of the tool point and concentration of the used electrolyte. As the work piece lies in close proximity (typically within 20mm) to the tool electrode, material removal takes place by melting and etching of the work piece. This material removal process mechanism is known as ECDM. ECDM process has the limitations such as surface defects due to localized overheating, which requires a suitable arrangement of intermittent cooling such as pulse power supply. Low material removal rate (MRR), low depth of penetration, overcut and taper in the hole are major problems in the ECDM. These may be due to lack of flow of electrolyte at tool point during machining. However, these problems can be minimized by a proper design of tool point of tool electrode. Tool electrode may be given a suitable movement in order to get better results of machining such as rotation. Tools are also vibrated ultrasonically to give linear movement. These tool movements result in reduction of taper, overcut and better surface quality of sidewalls.

Tool and its significance

The tool electrode has a significant role in the machining. The lesser area of the tool cross section is used for achieving higher current densities. Tools with pointedends are preferred geometries as they concentrate sparking action at the tool point. This results in better machining performances with quality surface of the work piece. The size of the counter electrode is kept as large as possible and material of this electrode must not react with the electrolyte used. The current density being less on counter electrode limits its anodic dissolution. Counter electrode should be shaped in such a way that distance between electrodes be constant while machining. A circular hollow pipe or ring can be used as anode surrounding the tool electrode. Such type of electrode can maintain a constant inter electrode resistance. This resistance should be reduced in order to minimize the time for formation of gas film as much as possible. Materials for both electrodes should be properly selected. The tool electrode material should have the following properties:

It should be rigid as possible in order to resist bending or misalignment during machining. The material should be chemically inert to the electrolyte used. Materials have excellent corrosion resistance and good wear resistance.The electrodes are made of stainless steel or nickel and preferred because these materials have excellent corrosion resistance, chemical resistance to electrolytes and minimum tool wear. Tool wear is negligible in ECDM, which occurs due to chemical etching and anodic dissolution. The spark activity at the tool tip may be a cause of some tool wear. No significant tool wear was observed and has never been quantified. The same tool electrode (stainless steel) can be used frequently. Fabrication of precise shape and size of tool electrodes is a difficult task. However, wire electrical discharge grinding (WEDG) is possible solution and an excellent and flexible method for micro fabrications of tool electrode. Anodic etching of tungsten is also another method for tool fabrication. Physical features of the tool electrode such as geometry; rotation and roughness greatly influence efficiency and accuracy of the ECDM process. The surface roughness of the tool is an index of quality of gas film produced during electrolysis. This influences thickness, stability of the gas film and power supply requirement for spark action also. Geometry of the cathode tip is a measure of dimensional accuracy of the machining structure produced by ECDM. Hence, tool design or configuration is important for ECDM process for improving machining efficiency and accuracy.

Tool electrode process parameters

Process parameters are defined as all those ECDM process variables whose variation affects measurable outputs (process responses). A particular type of variation in the physical feature of a tool, which can be observed and whose value influences more or less to the machining performance in terms of MRR, surface quality and dimensional accuracy, can be termed as tool electrode process parameters. All those process parameters, which cannot be covered in electrical and chemical process parameters, are classified as tool electrode process parameters in this article. Following are the different types of tool electrode process parameters: Shape or geometry of tool; Size or dimensions of tool; Surface roughness of tool; Material of tool; Rotation speed of tool; Machining time; Immersion depth of tool. The developments of these process parameters are classified into four groups due to the reason that some parameters and their impact on machining performance are similar in nature.

Classification of tool electrode process parameters

Tool electrode process parameters, which are interrelated to each other and similar in physical nature, are classified into one group. Shape, size, geometry and dimensions are interrelated features; therefore, these may be considered in one group and termed as geometry-based process parameters. Surface roughness of tool materials may vary due to their different crystal structures in spite of the same manufacturing process. Hence, surface roughness andmaterial of the tool are combined in one group, which are referred in subsequent sections as surface roughness–based process parameter. The motion (rotary or linear motion) of the tool and immersion depth of tool are considered in single group and referred as tool motion–based process parameters. The last group is a general group, in which all those features of the tool covered, which are not considered in above three groups such as machining time. The ECDM process involves submerging a glass substrate in an alkaline electrolyte, with the introduction of a tool electrode and a counter electrode. The tool generally serves as a cathode and is brought into close proximity to the machining site. A DC voltage is applied to the cell, and the potential drop across the double layer causes the electrolytic decomposition of water with hydrogen evolution at the cathode and oxygen evolution at the anode. As bubbles increase in size the buoyancy force exceeds the adhesive force, bubbles detach and a region of high current density is produced to initiate further bubble nucleation.

Above a critical voltage (around 30 V), the rate of bubble formation exceeds bubble detachment and the bubbles coalesce into a gas film, blanketing and insulating the electrode to cause resistive or Joule heating and vaporize neighboring water molecules. The gas film is over heated, aiding current transport and resulting in electrical discharges across the gas film with light emission, sparking. The discharges in combination with the Joule heating cause a high-level local heating radiating from the tool electrode tip.

IDENTIFY, RESEARCH AND COLLECT IDEA

Literature Review

The survey of past research investigations from different engineers and researchers, in the field of ECDM, have been enlisted as follows:

Basak and Ghosh (1996)

He investigated the mechanism of spark generation during Electrochemical Discharge Machining (ECDM) and observed that spark discharge took place at the bottom edge of smaller electrode across the gas bubble layers in ECDM process. The authors developed a simplified model to predict the characteristics of the material removal rate for varying input parameters with the objective of finding the possibility of enhancing the capability of the process. With the help of the model the critical voltage and current required to initiate discharge between the electrode and electrolyte were estimated. The authors also observed that when the voltage applied across the electrodes increased, the rate of bubble generation also increased. The authors described the electro discharge phenomenon as a switching process between the tool (one of the electrodes) and the electrolyte. The authors compared theoretical-predicted values with the help of mathematical model and showed that the critical voltage increased slightly with tool diameter.

Ghosh (1997)

He discussed the principle and possibilities of Electro chemical Discharge Machining and described that the electric discharge was primarily due to switching phenomenon and not to the breakdown of the gas in the blanket. The author explained the mechanism of ECDM by ECD phenomenon and suggested that a resistant layer developed around the tool electrode was mostly used as cathode and H2 evolved in the form of very fine bubbles. Electrochemical discharge starts only when the applied voltage reaches a critical value which depends on the type of electrolyte and its concentration.

The author also suggested that blanketing could be a major factor in the occurrence of electrochemical discharge as both H2 evolution and vapor production through boiling depend on the power only and by proper controlling the location of heat source, the required shape of the work piece could be achieved. From the experiment it has been showed that the hemispherical bubbles covered the surface completely. The authors documented that the breakdown of insulting layer was analogues to the switching phenomenon and studied the process capability of ECDM process.

Bhattacharyya *et al*. (1999)

Discussed the basic material removal mechanism in the ECDM process for the effective machining of non-conducting ceramic materials and carried out investigation on the effects of various process parameters such as the applied voltage; concentration and type of electrolyte; the shape, size and material of the electrodes. The authors stated that the material removal took place due to the combined effects of electrochemical (EC) reaction and electrical spark discharge (ESD) action and it was found that two types of reactions usually occurred in the system (i) electrochemical reactions at the electrode, e.g. gas evolution, plating, electrode dissolution and oxidation, etc.; and (ii) chemical reactions in the bulk of the electrolyte, e.g. chemical combinations, the complex formation or precipitation reactions for precipitates and sludges, etc. He showed that the material removal rate increases with increase of the applied voltage at different electrolyte concentrations and MRR was not very significant, but at higher voltage (i.e. 80, 85 and 90 V).The influence of electrolyte concentration was more predominant as the rate of gas bubbles generation increased, resulting in a greater amount of spark generation in the sparking zone, which in turn increased MRR.

Further the authors observed that at higher applied voltage for different electrolyte concentrations, over-cut was higher because of more possible stray sparking at the side wall of the tool tip. the tool tip geometry greatly influenced the material removal rate and over-cut criteria in the ECDM system .MRR for straight side wall-flat front, taper side wall-flat front and taper side wall-curvature front tool tips were 0.056, 0.154 and 0.248 mg/min, respectively. Finally the authors concluded that though the machining rate of ceramic materials was low in the ECDM process but the method is more effective for cutting those non-conductive materials considering the capability of machining a complex profile.

Jain *et al*. (1999)

He developed a model for ECSM as a phenomenon similar to that which occurs in arc discharge and evaluated material removal rate by finite element method modeling the problem as a 3-D unsteady state heat conduction problem. The authors explained that when the two electrodes were of grossly different sizes then beyond a certain value of applied voltage, electric sparks appeared at the electrode- electrolyte interface on the smaller electrode and the cell current drops. In this study, material removed per spark was computed by multiplying the volume of the melted/softened material by its density and the volume of the softened material/crater was computed by generating the isotherms for the temperature equal to and above the softening/melting temperature. The modeling of the electrochemical discharge phenomenon were done by proposing a new theory called valve theory which was used to compute material removal rate (MRR) and the proposed ‘valve theory’ was capable of satisfactorily modeling the discharge phenomenon in the ECSM process.

Kulkarni *et al*. (2003)

He investigated the basic mechanism of material removal in ECDM process through experimental observations of time-varying current.

The material removal mechanism was also explained with the help of SEM photographs of spot hit by a single spark.

Chenjun Wei &KaizhouXu& Jun Ni & Adam John Brzezinski &Dejin Hu (2011)

They have investigated a finite element based model for ECDM drilling in discharge regime is presented. Material removal subjected to a single spark was simulated using finite element method.a finite element based model of ECDM drilling in discharge regime is presented.

McGeough (2011)

He 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, found that the probability of occurrence of ECM and EDM phase simultaneously in ECAM was very less.

Doloi B (1997)

He 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. He 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).

Pankaj Kumar Gupta, AkshayDvivedi, Pradeep Kumar

They represented phenomenon of material removal as hole overcut (HOC) with the help of ECD from cylindrical tool. Investigations were performed for working gap (between tool and work piece) to result minimum HOC. Results revealed reduction in HOC at minimum working gap till the tool comes in contact with work piece. The maximum limit of tool work piece gap was 250 μm, beyond which no material removal was observed.

C.S. Jawalkar, Apurbba Kumar Sharma, Pradeep Kumar (1997)

They have given a critical review on materials machined by ECDM under the prevailing machining conditions; capability indicators of the process are reported. Some results obtained while performing experiments in micro-channeling on soda lime glass using ECDM are also presented. In these experiments, Tool Wear (TW) and Material Removal (MR) were studied using design of experiments and L–4 orthogonal array. Experimental results showed that the applied voltage was the most influencing parameter in both MR and TW studies. Field emission scanning electron microscopy (FESEM) results obtained on the micro channels confirmed the presence of micro-cracks, primarily responsible for MR. Chemical etching was also seen along the edges. The Energy dispersive spectroscopy (EDS) results were used to detect the elements present in the debris and specimens.

C.S. Jawalkar, Apurbba Kumar Sharma, Pradeep Kumar (2012)

They have carried out detailed parametric study using the standard L9 orthogonal array. Influence of process parameters, namely electrolyte concentration, applied voltage, distance between electrodes and time of current flow on response parameter, i.e., MR were analyzed. The results showed that NaOH was more efficient as compared to NaNO3. The results on MR showed that all parameters were significant and applied voltage was found to be the most influencing parameter (70.14%). Field emission scanning electron microscopy (FESEM) and debris analysis were further carried out to study the performance of the ECDM process.

B.C. Schmid, A.N. Finn and J.C. Young (2012)

They have determined the linear thermal expansion from 25 degree centigrade to the "critical" and "softening" temperature for 19 soda silica and 90 soda-lime-silica glasses by the interferometer method.

STUDIES AND FINDINGS

As per above literature review there is no data for modeling and simulation of soda lime glass through ECDM process by ANSYS. Hence, same is undertaken in this thesis.

Consideration with respect to present study of ECDM

In ECDM process, the work piece is dipped in an electrolyte like NaOH. The tip of the tool-electrode is dipped inside the electrolyte by few millimeters and counter electrode of larger size (about a factor of hundred) is placed few tens of millimeters (centimeters) inside the electrolyte. When a pulsed voltage or DC power is supplied between electrodes, electrolysis occurs at low voltages that result in formation of hydrogen bubbles at tool electrode and oxygen bubbles at the counter electrode. The bubble formation increases with the increase in the applied voltage. Beyond a critical voltage, the formation of gas film takes place around the tool electrode due to coalescence of the bubbles. The gas film isolates the tool from the electrolyte and builds sufficient electric resistance to generate the electrical discharge. If the work piece is placed near the vicinity of the discharge zone, machining does take place in the form of thermal erosion and chemical etching. In the present work, a 3D finite-element model has been developed to determine the temperature field developed due to heat generated by a spark that leads to MRR. Further, the temperature plots in the zone of influence of single spark and number of sparks per unit time were used to estimate thermal damage.

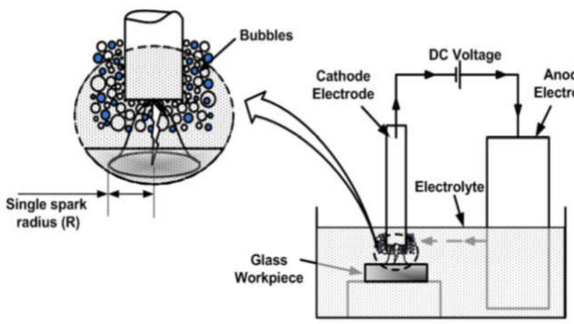


Figure 3. Schematic diagram of electrochemical discharge machining

In the present work, a 3D finite-element model has been developed to determine the temperature field developed due to heat generated by a spark that leads to Thermal damage. Further, the temperature plots in the zone of influence of single spark and number of sparks per unit time were used to estimate thermal damage. Results of the developed model were compared with experimentally obtained values as reported by other authors.

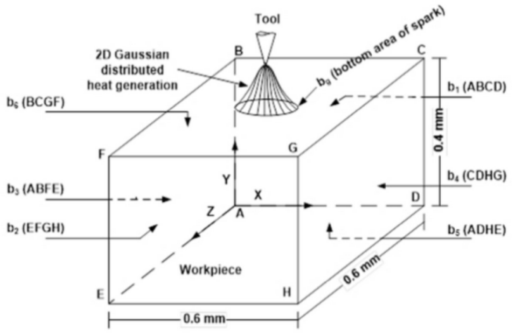


Figure 4. Geometric model with boundary conditions

A finite-element model (Figure 3.2) was developed to analyze Thermal damage caused by one spark, which causes heat input to the work piece. The work piece was modeled in 3D with a dimension of 0.6×0.6×0.4. A cone part was considered glued on the top surface of the work piece. This bell-shaped part was assumed to be representing the shape of a spark. Boundaries b1, b2, b3, b4 and b5 were considered insulated thermally since heat transfer cannot occur across these boundaries because the thermal conductivity of glass is too low and spark duration is also too short. The area bq covered by the bottom of the spark on the top surface of the work piece, receives heat from the spark. The remaining portion of the top surface (i.e. b6 - bq) was considered to be thermally insulated similar to other boundaries.

Formulation of the spark region

The spark region was constructed using the bell curve. The bottom radius of the bell curve was taken as the spark radius while the height of the curve was derived by a trial-and-error method. Five models were constructed with different curve heights (0.05, 0.1, 0.15, 0.18, and 0.17 mm) to find out the suitable curve height. Each trial model was simulated for the same set of working conditions. The temperatures at the center of spark on top surface of the work piece were compared with the temperatures reported by Bhondwe *et al.*

The temperature 17071.1 K (Table 1) was resulted from the fifth model of spark height 0.17 mm and was found to be nearer to the temperature (around 17000 K) as given by Bhondwe *et al*. Hence, the spark height was taken as 0.17 mm for further analyses.

Boundary conditions

As the work piece is immersed in the electrolyte before the start of the process, the temperature of the whole domain ABCDEFGH was assumed to be at room temperature (To). Hence, T = To in the work piece domain at t = 0. Boundaries b1, b2, b3, b4 and b5 were considered to be insulated as the temperature gradient across these boundaries is very less when compared to incoming heat boundary bq and is almost negligible. On the boundary b6, the total heat qg, produced by the spark was passed to work piece through the area of bq. In the present work the Gaussian heat generation distribution was used and accordingly the heat generation calculation expression is derived as

$$q_g = \frac{4.45 E_p V I}{Volume\ of\ spark\ region}$$

Where qg is heat generated V is voltage applied and I is current. For calculating volume of spark region the spark diameter was taken as 300 µm, which is based on experimental results reported by Kulkarni *et al*. Wüthrich and Fascio25 had reported that the duration of spark is in an order of 100 µs when a constant DC power is applied. Therefore, the constant value of 100 µs was used as the spark duration in this model.

Estimation of Thermal Damage

In ECDM, the material removal and thermal damage is primarily caused due to melting and ablation when the discharge takes place across the hydrogen gas film generated in the reaction of electrolysis. Actually, the gas film generation is a complex phenomenon and is based on the process of randomly generated hydrogen bubbles. However, the analysis of hydrogen gas film becomes challenging because of the problem of locating the nucleation site of the hydrogen bubbles over the tool surface; it is a highly stochastic process. Thus, the material removal and thermal damage calculation is usually carried out for single spark to simplify the situation. Assuming that the distribution of energy is equal among the sparks, the thermal damage can be calculated as the thermal damage by one spark and total number of sparks per unit time; this assumption is based on the work of Bhondwe *et al*. It was also assumed that the discharge occurs only at the tip of the tool and only one spark is generated at a time, and sparks occur consecutively at the same location. In ECDM, the thermal damage is related to temperature rise in the work piece due to spark. Therefore, the thermal damage criterion can be taken as; Transition temp>thermal damage temp>Melting temperature This criterion says that the work piece material will be thermally damaged when its temperature is between transition temperature and melting point of glass i.e. soda lime glass

Assumptions for Simulation

The following assumptions were made with respect to the ECDM process in order to simplify the model and are commonly used by various authors:

- The properties of work piece material are isotropic and homogeneous.
- For each discharge, only one spark is produced at the tip of the tool.
- 3 A fraction of total heat of sparking was dissipated into the work piece as the heat zone is surrounded by electrolyte.
- Duration of each spark was assumed to be identical.
- Assumed ejection efficiency is of 100%.
- Tool wear, drop in electrolyte level due to evaporation of water and chemical consumption were neglected.
- thermal damage by cavitation effect and deposition due to recast layer on the machined surface were ignored.
- Shape of heat distribution is identical for all sparks.

Analysis of ECDM process using Ansys APDL software

The ECDM process on work piece is verified by analyzing the experimentally obtained result with the analyzed result with the help of Analysis software Ansys APDL. Analysis is done to verify the results achieved by following these set of steps. This analysis comes under the category of thermal analysis. While performing the thermal analysis of the proposed work, following steps are followed-

1.Problem Specification-
The proposed work is verifying the Electro chemical discharge machining. This is achieved by thermal analysis of work piece using analysis software APDL version 14.0. The process under consideration is Electro chemical discharge machining (ECDM).

- Work piece material is Soda lime glass
- Tool used is stainless steel.
- Electrolyte used is NaoH.

Problem Description

This is a transient heat transfer analysis of ECDM process.
The objective is to track the temperature distribution in the ECDM process, single spark, in the thermal damage zone of work piece material, which occurs over duration of single spark. The ECDM is carried out in rectangular section work piece of soda lime glass, size considered is 0.6mmx 0.3mm (sectioned) x0.4mm.

Prepare for a Thermal Analysis

Just before starting the thermal analysis of the proposed work piece we need to specify preferences that help in analysis.

To Set Preferences these steps are followed:

- Click on the Main Menu option shown if figure below.
- Select Preferences.

(Check) "Individual discipline(s) to show in the GUI" = Thermal

(OK), in the following dialogue box

Input Geometry

In this step, a new model is to be created. The ANSYS main menu for that is shown below. Further following these steps

- Click on Preprocessor,
- Then modeling,
- Then create,
- Then select volumes (as we are working on 3D),
- Then blocks,
- Finally click dimensions and give suitable values.

3D model is generated after following these results which is analyzed in AnsysAPDLsoftware.

Define Materials

Next step is to define the material.

For this following steps are followed in the main menu

- Click Preprocessor,
- Material properties,
- Material models,
- Thermal

After this we have to assign suitable values for both the materials, i.e. spark and work piece.

- For the spark- hydrogen flame is considered/ assumed
- Work piece is soda lime glass.

The values assigned are as below in the table:-

Table 1. Values assigned for the material.

Attribute	Soda lime	Hydrogen/plasma
Density (kg/mm^3)	0.0000217	0.00000000133
Conductivity (w/mm-k)	0.00166	0.00023
Specific heat (j/kg-k)	670	50000
Melting temp (k)	1673	-

Gluing

Gluing is required to make contact between two or more bodies. Gluing is done to associate the two bodies so that the effect of heat transfer from one to another can be analyzed.
Steps for gluing are as follows-

- Click preprocessor,
- Modeling,
- Operate,
- Booleans,
- Then glue.

Generate Mesh

Now the model is meshed for analysis. Meshing is required to obtain results with greater precision. Meshing is dividing the model into nodes and elements for further analysis and obtaining the results.

These steps are followed in meshing

- Click preprocessor,
- Meshing,

- Then Mesh tool.

Apply Loads

In this step we apply all the loads and boundary conditions given for ECDM process.

These steps are followed to apply the loads on the model

- Click loads
- Define load,
- Apply,
- Thermal,
- Then Heat generation.

Obtained Solution

For different values of voltage and current at 2.3 amp different values of heat generation were calculated and are shown below in the table.

Table 2. Heat generated values for different voltages

Voltage	Heat generation
40	19760.42
45	22230.48
50	24700.53
55	27170.58
60	29640.63
65	32110.69
70	34580.74

Above values of heat generation were used in the Ansys APDL software for animation and values of Thermal damage are obtained as below-

Review Results

The animated results of ECDM process for given heat load is given in figures as given below. These figures give thermal damage, in case of single spark, for various input heat conditions corresponding to voltage 40 volt, 45 volt, 50 volt, 55 volt, 60 volt, 65 volt and 70 volts

Conclusion

The following conclusions could be made

- The single spark model was developed and simulated for thermal damage.
- Single spark volume was estimated to be 0.015854 mm3
- Maximum value of thermal damage=0.0405 mm3 and Minimum value of thermal damage=0.0191 mm3

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