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ELECTROCHEMICAL MACHINING-A REVIEW

Part 1.: Theories & Applications

A. M. ABDEL MAHBOUD

Lecturer, Prod. Eng. and Mach. Des.Dept.
Faculty of Engineering and Technology
Menoufia University
Shebin El-Kom,
Egypt.

INTRODUCTION

Electrochemical machining (ECM) has been initially developed to machine alloys which are exceedingly to machine by conventional methods. It basis is the phenomenon of electrolysis, whose laws were established firstly by Faraday in 1818 - 1824 (1-2).

However, ECM turns out to have been first proposed in 1929 with the basic patent of Gusseff (3). Moreover, Burgess (4) in 1941 presented a paper outline a number of possible ECM applications. In 1946 electrochemical cutting off machine was described (5) but the application of ECM methods for actual machining seems to have been first put to general use about 1950 in the form of electrolytically assisted grinding (6). In 1959 ECM was put forward in the form of a commerical apparatus for regular industrial applications by Anocut Engineering company of Chicago (2 & 7).

Since that date large numbers of publications were established. Thus, the need has been felt to review the state of the art of ECM. Two main articles of review have been published since 1977 (8,9). Both the two were devoted to ECM principals, dynamic fundamental of the process, electrochemistry phenomena, electrolyte properties, dissolution kinetics, tool design, machined surface nature and ECM machinery, as well as, brief describtion of both practical applications and its theories.

Thus, and attempt to review ECM literature regarding its practical application and theories was imperative. The objective of this paper is to demonstrate the state of the art of ECM regarding its practical application and theories.

Because the review of ECM literature yielded a large number of papers. Two separate papers were prepared covering the topics:

I Theories and application.

II- Surface study.

The most important ECM modes are drilling, grinding, cutting off, broaching, wire cutting, deburring etc.

1. CAVITY SINKING, HOLE DRILLING, AND BORING

Many theories have been presented for analysing such processes. Konig et al. (10) showed that the side gap is dependent on frontal gap, tool corner radius, effective tool land and working parameters. Moreover, all machining conditions were discussed regarding their optimizations with the help of nomograms. While in another paper an iterative method was used (11) to obtain the progressive workpiece contour after an elemental time. Also Konig et al. (12) indicated that for sharp corner tools, the profile of the side gap is parabolic.

Deitz et al. (13) indicated that besides the parameters discussed by Konig et al. (10), it is necessary to take into account the amount of hydrogen as well as the electrolyte pressure (14) they discussed the determination of the side gap by replacing the curvature at the cylindrical tool bottom by a tangent polygon course and the appropriate gap was determined.

Ippolite et al. (15) presented a mathematical model for the determination of the workpiece profile and considered the process independent variables to be electrolyte conductivity, volt/feed rate ratio and tool land. Note et al. (16) found that even if using a non-insulated electrode, a straight hole can be obtained when using a sodium nitrate solution and taking into account the amount of oxygen evolution. Noble et al. (17) derived a simple mathematical approach for estimating the radial overcut. Based upon dimensional analysis the importance of the ratio between the feed rate and flow rate was illustrated. Their results showed the beneficial effect of using a reverse flow system for improving both surface finish and dimensional accuracy . In a report presented by PERA (18) the case of a square unradiused tool was studied with the objective of determining the magnitude of overcut. It was concluded that the radial overcut could be defined as a function of frontal equilibrium gap and tool land. De Barr et al. (2) and Kawafune (19) used analogue models of the electric field to predict the workpiece goemetry, Tipton (20) studied the use of the "Cose θ" rule for predicting the workpiece profile during equilibrium state. While the analysis worked out by Thorpe (21) proved the in adequacy of the "Cose θ" law especially when large curvatures were handled. Also Thorpe (22) presented a mathematical model of the side gap kinematics.

The validity of an electric field approximation model to obtain the gap profile was discussed by Tsuei et al.(23). The effect of machining conditions on the stock removal rate and production accuracy of produced holes in hardened steel and Widia was investigated by Abdel Maksoud (24). Jain et al. (25-27) presented three models called modified ECM theory, finite element technique (FET) and resistance model for predicting a square drilled holes. A parametric study which highlights certain guidelines for tolling was also involved. Klingert et al. (28) used a trial and error procedure to obtain the workpiece shape while using a numerical method to solve the field equations for two electrodes.

Lawrence (29) discussed the prediction of the tool and workpiece shapes using an approach based on analysing the potential and current distribution in the inter-electrode gap. Nanayakkara et al. (30) recognized that the calculation of the shape produced by a tool or the determination of the tool shape was not easy to find.

The work reported by Maeda et al. (31) regarding cavity sinking operations indicated that to obtain small overcuts, high current densities and low working voltages should be applied. Moreover, Kurafuji (32) studied the main parameters affecting the reproduction accuracy with prismatic tool shapes in parallel flow methods.

An over simlified assumption was adopted by Ghabrial (33) for the prediction of the processed shapes. Comparison with previous analytical and experimental results yielded widence for the useful application of such simple approach in practice.
The majority of the analytical models described above are based on several assumptions. However, a new term called correction factor was introduced by some workers as follows:

Dietz et al. (34) showed that when the radii of curvature are comparable to or even smaller than the average cross-sectional shape dimensions, some correction factor should be introduced. A comprehensive mathematical model based on the complex variable technique was made by Collett et al. (35) for obtaining the drilled shapes. They showed the correction factor was 0.73 for insulated tools and 1.7 for non-insulated. Hewson (36) extended the work of Collett and employed the conformal mapping tedhnique for the analysis of two dimensional machining operations.

On the otherhand Kawafune (37-38) studied the progressive relationship between the tool and workpiece in a die sinking process starting from an initial flat surface and showed that the correction factor is between 1-1.2, whereas PERA (18), takes it 1.7. Moreover Lawrence (29) showed theoretically and experimentally that the correction factor amounted to 1.7, where as Ippolito et al. (15) takes it 1.5.

Ebeid (39) introduced the voltage/feed rate ratio as an important factor controlling the side overcut and stated that the correction factor is not-constant as mentioned before, but depends upon the voltage/feed rate ratio. The same results were obtained by Hewidy and Abdel Mahboud (40) when drilling hexagonal holes.

The above research workers have analysed the characteristics of frontal and side drilled zones, but little information concerning the characteristics of stagnation and transition regions. Jain et al. (41-42) presented an experimental finding for the shape and size of the transition zone for blind holes. Their results have realized an exponentional type of relationship between the tool corner radius and copied raius. Whereas Konig et al. (10) developed an empirical formula for the corner region as well as for the side gap region. Their equations permit an accurate calculation of the side gap in the corner region for radii common in practice.
Larsson et al (34) studied the validity of using the height of the spike produced in stagnation zone of an unisulated drill tool as an index of dimensional control, taking into account polarization curves with current density. The reverse problem of ECM processes i.e. determination of tool geometry for a specified workpiece shape was analysed by many workers. It is noted that the design problem is not unique since any one of the equipotential curve lying in the gap between the tool and workpiece can be used to machine the workpiece.

Krylov (44) analysed the design problem of EC drilling tools using an analytical function to express a famílly of curves to define the tool profile. Mereover, Alekseev (45-46) assessed the error of the tool profile.

based on the assumptions that the current dessity was linear and normal to the cathode surface. The tool design problem is formulated by the inverted approach in which the spatial coordinates are treated as the dependent variables on the plane of the complex potential was discussed by Nilson et al. (47-49).

Jain et al. (50-51) used the finite element technique to design and analyse complicated ECM tools. Furthermore, the validity of ECM tool design by computer aided design (CAD) was reported (52), Collett et al. (35) analysed the tooling design problems by using conformal mapping transformations to solve the potential field. While Tipton (53-55) discussed the cathode design for cavity sinking by introducing a finite difference solution of the laplace equation for the electric field.

In boring process, it is customary to enlarge the predrilled hole (circular and non-circular) and the same time finish it by correction any error in the profile. However, little work has been done toward the application of EC boring (56-57). Jain et al. (57) discussed the beneficial effect of using a bit tool for the boring process. Theoretical and experimental investigations revealed that there is a significant improvement in dimensional accuracy as compared to the bare tools.

A new concept of ECM drilling process is the use of composite programme controlled (CPC) ECM tool (58) to produce various workshapes by controlling the surface potential. Theoretical and experimental investigations were carried out by Reghuram et al. (59) with an annular composite ECM tool with constant voltage applied to three sections with different duty cycles controlled by a relay circut.

2. FINE HOLE DRILLING

Little work has been established concerning deep and fine hole drilling.

Bannard (60) illustrated four categories for EC fine hole drilling namelly, Shaped Tube Electrolytic Machining (STEM), Capillary Drilling (CD), Electrostream Drilling Liquid Jet Drilling. The problems associated with the hole geometry and with surface finish were discussed. Jackson et al. (61-62) discussed the ability of machining straight or curved holes with depth to diameter ratios of 200 :1 by Shaped Tube Electrolytic Machining (STEM). Moreover, a description of the Liquid Jet fine drilling was illustrated by Gardner et al. (63). The hole produced was found to be four times the diameter of the jet, which depends upon the throwing power of the electrolyte. Also high applied voltage (400-800 V) should be utilized.

An interesting development from the STEM technique has been made by the General Electric Company (8) in the Electrostream process. A sulphuric acid based electrolyte about 20 % concentration was used and applied to drill hole sizes from 0.5 mm. diameter or less. High voltages were used above 350 V which promote machining action in the "glow discharge" regime. Bellows (64) indicated the capability of ECM process for drilling 0.125 mm. diameter holes to a depth of 12.5 mm. It is reported that on a production basis, depths of 25 mm. at 50:1 depth/dia. ratio are being achieved with tolerance on the hole diameter of ± 5 %. Glew (65) described the technologyical usage of Capillary Drilling (CD) method for producing deep holes ranged (0.25-0.4)mm. diameter and (6-16) mm depth in turbine blades when using a diluate nitric acid solution as electrolyte at 100 volts. While Larsson et al. (66) studied the problem involved in drilling an aluminium vanadium titanium alloys. Rotation of the workpiece with respect to the drill was found necessary to obtain straight holes Jones (67) demonstrated the problems accompained with the insulation for fine hole drilling tools with glass material.

3. ELECTROCHEMICAL GRINDING (ECG)

There are two main types of ECG. The first one is based on both the anodic dissolution and abrasive action and the second one is based only on the anodic dissolution, which can be considered as EC milling.

ECG applications were described by the United Airlines Inc. (68) for the overhaul of jet engines. The process is used for grinding the interlocking surfaces accurately on turbine blade shrounds and finishing honeycomb seals without introducing distortion or burrs.

Colwell (69) and others (70-77) studied the effect of numerous parameters on the machining performance with economical comparison of ECG and conventional grinding. A different approach was published by Colwell (78). On basic of experimental results he concluded a maximum current criteris for the process optimization as to gain maximum total removal rate. This work does not refer to surface finish, ratio between mechanical and electrical machining rates or process variables limitation and sparking. Whereas a desiging of an automatic system which allows optimal operating parameters according to a desired criterion was discussed by Lenz et al. (79). The advantages of such technique lines in its flexibility as well as, in the including of many process parameter in the control. Therefore, the need of trained worker to operated ECG machine is eliminated.

Furthermore, models of ECG process were developed by Backer et al. (80), Cole (81-82) and Kaczmarek et al. (83) for separating the total removal ratio into mechanical and electrochemical components, based on the assumption that the mechanical and electrochemical removal processes proceed independently. Levinger et al. (84) presented an investigation in ECG of WC-CO cemented carbides, with particular consideration of the heterogeneous nature of the electrochemical phenomena for WC-CO cemented carbide. Also selective electrochemical etching which reduces the required mechanical grinding forces was observed and discussed by Geva et al. (67) when grinding of cemented carbide surfaces. Brainard et al. (85) found that when scratching with diamond tool that the abrasion resistance of WC-CO cemented carbide was produced by chemical etching of the cobalt method binder from the surface. The applicability and limitations of ECG profile (rectangular, semicircular, trapezoidal and triangular) have been investigated by Kaldos (86) for carbide and hardened high speed steel tools. Optimum working conditions are presented in the terms of depth of cut and workpiece accuracy. While Kremer et al. (87) assessed the influence of driving parameters on ECG surfaces (flat and profiles) which were characterized by technological dimensions, metal removal rate accuracy, surface integrity and economical dimensions regarding their optimizations.

An investigation of the surface integrity and repeatability of overcut for conditions of removal when associated with mechanical contribution was carried out by Atkinson et al. (88) in peripheral ECG. Frisch et al. (89) investigated the residual stress distributions in thin steel strips subjected to peripheral ECG at varying shallow set depths which yielded compressive and tensile residual stresses. Whereas, the variation of total removal rate with current has been investigated by Perry (90). Also Noble (91) established the expected amount of mechanical contribution, The effect of tool direction rotation on the productivity was illustrated by Manol (92). Chetty (93) presented the preliminary investigations on smoothing of anodic surface irregularities. Effect of machining time and influence of $NaNO_3$ and NaCl solutions using relocating machining fixture were highlighted. Also important parameters and tool lives of electrolytically and conventionally ground tools were compared by Gase (94).

The force affecting the grinding wheel wear was studied by Pryakhin (95). De Barr (2) showed that by using aluminium wheel and sodium nitrate electrolyte solution tungsten carbide tools can be ground without the use of abrasive. Bejar (97) studied the influence of concentration, temperature, electrolysing current, on metal removal rate, surface finish and dimensional accuracy during grinding high speed steel with rotary copper wheel without abrasive. Two types of electrolyte solutions (NaCl, $NaNO_3$) where used. Gurklis (98) discussed carefully the effect of the electrochemical metal removal process on the mechanical properties especially on fatigue strength. Four processes were involved namely ECM, ECG, EC polishing and EC milling. General characteristics and applications of the four methods were presented.

4. EC HONING

A study of EC honing by Victor et al. (101) demonstrated the possibilities of performing corrections in cylindrical bores by controlling the flow of electrolyte in the working gap. Whereas the principles of EC honing were illustrated by De Barr (2). Pandlett (102) proved that EC honing has much higher stock removal rate than either conventional honing or internal ECG. Also Nurai (103) stated that in EC Honing the temperature ranged from 25-40°C. At these low temperatures, no burring, or small cracking or distortion of most metal surface can occur. Hence, ECG and EC honing seem to be similar processes in which no burrs are produced. Therefore, it is useful for application where burrs must be avoided.

5. EC TURNING

A 300 A ECM lathe was described in 1962 by Williams and Stroupe (104) together with a number of applications. Wilson (7) outlined the basic concepts of a segmental EC turning tool design. Hofstede et al. (105) described the phenomena observed in EC turning when three type of electrodes (concave, convex and flat) were used. Theoretical and experimental investigations of current distribution, effective feed rate, and choice of optimal electrode configuration were involved. Moreover, Dietz et al. (106) presented a mathematical modeling of the field strength distribution. The interrelation between the operating parameters were also discussed.

6. EC CUTTING OFF

De Barr (2) stated that ECM can be used for sawing or slicing bars or billets. It is particularly useful for cutting material such as tungsten and its alloys which are difficult to be cut by conventional methods.

7. ELECTROCHEMICAL BROACHING (ECB)

ECB as a new technique of ECM (8) could be listed under non equilibrium process, where a constant current density cannot be achieved. Starting from pre-drilled holes Kremer et al. (108) studied the parameters controlling the ECB for producing square and hexagonal holes regarding accuracy and surface integrity. Whereas Geworkian et al. (109) broached square holes in a titanium alloy with 300 mm length. Ghabrial et al. (110) presented a simple theoretical analysis for predicting the workpiece profile using both square and triangular ended broaching tools taking into consideration the variation of the boundary conditions, besides estimating the power consumption. Analysis and definition of progressive shape formations for certain arbitrary tool design were also included. While Kohail et al. (111) analyzed the problems accompanying the application of ECB for producing airofoil and parallellogram solts. A comperative study between ECB and stationary ECM cutting were performed by Sinbel (112), regarding sizing, rate of metal removal, power consumption and surface quality for circular holes.

8. ELECTROCHEMICAL WIRE CUTTING (ECWC)

ECWC has the advantages of low power consumption and simplecheap tooling systems compared with other ECM processes. Jain et al. (113-115) analysed the ECWC process when using a rectangular cross-sectional wire. Three different theoretical models were presented. Moreover, Chickamouri et al. (116) discussed the ECWC process for the three dimensions with curved wire, also some examples were reported. The application of sawing with wire was investigated by Degenhardt et al. (117) the process was found to be efficient and is deemed useful for cutting high cost metals with low material losses while the cut surfaces remain undamaged, accuracy is not good as in EDM wire cutting. A parametric study of ECWC was performed by Ghabrial et al. (118) for circular and rectangular cross - sectional wires. A simple mathematical model and optimum machining conditions were found.

While Streeniya (119) used cathode tools in the form of tubes for making three dimensional slots, Kargin (120 - 121) examined the efficiency of such tubular cathodes for the formation of semi-circular, rectangular and triangular surfaces. Noble et al. (17) derived a mathematical approach for obtaining the overcut in drilling using titanium tubular electrodes. The most important parameters affecting the process accuracy were discussed.

9. SINGLE POINTED CATHODE

One of the main future simplifications of ECM tooling system is the use of single pointed tool capable of cutting any contoured component by controlling the relative movement between the tool and workpiece. Some preliminary work at the Massachusetts Institute of technology in U.S.A. and at the University of Leicester has been undertaken successfully, demonstrating the fundamental feasibility of this concept (8). Moreover, the interacting parameters affecting the reproduction accuracy of circular holes produced by single pointed cathode were studied by Abdel Abdel Mahboud (122).

10. EC DEBURRING

Stationary ECM proved to be useful on the industrial scale. It is very active in deburring and embossing, as well as, in the internal polishing of different castings. Graham (123) presented a theoretical and experimental investigation for stationary cutting. Particular attention is given to establishing metal removal rates and the manner in which the initial surface texture is modified. Maeda et al. (31) introduced the idea of using gas-electrolyte mixtures with which they obtained good dimensional accuracy. Whereas Senecky et al. (124) and Ghabrial et al. (125) used air electrolyte mixtures which also improved machining accuracy, while diminishing sparking and formation of striations and smuts.

Chikamouri et al. (116) showed that the electrochemical machining in a stagnant electrolyte was realized with the use of pulsating current. Three examples of drilling, deburring and wire cutting were illustrated. Moreover, they studied the effect of the change of current pulses during machining. The disadvantages of the ECMSE is that the feed rate as well as the electrode area is limited to be relatively small.

EC deburring is a process for selectively removing burrs that are inaccessible when using other general purpose finishing processes. Bernard (126) described the equipment needed for a simplified EC deburring process, which has major applications within the hydraulic and pneumatic component industries. Some industrial applications of EC deburring such as forged aluminium fuel control system body, cast iron turbo charger housing, case hardened steel constant velicity joint, low carbon steel heater tube and forged connecting rod were illustrated by Graham (127). Compared with manual techniques cycle times may be reduced by up to a factor of 5.

Geworkian et al. (109) stated that in order to increase the EC deburring capacity, multi-station cathode devices are required. Kurt et al. (128) showed some automatic and semi-automatic EC deburring machines for saving labour costs. Moreover, the design of machines and equipment needed for EC deburring and EC contouring is identical.

11. PULSED ECM PROCESS

A method that has been used in ECM to bring about the breakdown of protective anodic films is the use of pulsed current (129-138). The feasibility of using pulsed current in ECM at relatively low electrolyte flow rate has been investigated by Datta et al. (129). Experimental results for high rate dissolution of nickel in 5 % NaCl concentration, in a flow channel cell under steady state and pulsed current are presented. Optimization of the process parameters were also involved. Theoretical expressions were derived for predicting electrolyte heating, mass transport and gas evolution. Realization of the PECM process was carried out by Kozak et al. (130) Effect of machining parameters, shape of voltage pulse, input pressure, width of gap and pulsed time on the workpiece accuracy and metal removal rate and its associated problems were discussed. Whereas in another paper (131) the advantages of PECM were ahowed. Moreover, mathematical models for the PECM process were described taking into account the non steady physical phenomena in the space of the electrodes (116). Shikate et al. (136) claimed that the use of pulsed current allowed passivating electrolytes to be used. An estimate of the effect of concentration polarization was made (137) from which the shape of the optimum pulse cycle was calculated. Sedykin et al. (138) claimed that closer dimensional accuracy could be achieved by using a gap pulse feed back system.

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