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ELECTROCHEMICAL MACHINING: REVIEW OF HISTORICAL AND RECENT DEVELOPMENTS

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ABSTRACT

The new materials and alloys which have been developed for specific uses possess a very low machinability producing complicated geometries in such materials become extremely difficult with the conventional methods. Hence, Non-traditional machining has evolved due to the need to machine exotic engineering metallic materials, composite materials and hightech ceramics. Electrochemical Machining has been accepted worldwide as a major process in manufacturing and is capable of machining geometrically complex or hard material components, not having the residual stresses and tool wear that are precise and difficult-to-machine. In this paper historical developments in the field of Electrochemical Machining(ECM) process and its recent developments associated with the effect of process parameters, parametric optimization methods, MINITAB software respectively on material removal rate, surface roughness, microstructure, operating, tooling, maintenance cost ,Quality has been discussed. The scope for future investigation has been highlighted.

Keywords: PECM, Minitab, Taguchi Method, ANOVA, S/N Ratio, STEM, JECM, Hybrid ECM

I. INTRODUCTION

Electrochemical machining (ECM) is one among the non- traditional machining processes in which material is removed by dissolution of the anodic workpiece during an electrolysis process. A D.C. voltage of specified magnitude is applied between the shaped cathode tool and an anode workpiece. The electrolyte (like- NaCl aqueous solution) flows at high speed (12-65 m/s) through the inter-electrode gap (0.1-0.5 mm). The current density is usually 15 to 200 Amperes per cm square. The dissolution rate of the anode, which is governed by Faraday's laws of electrolysis, depends on the electrochemical properties of the metal, properties of electrolyte and supplied electric current/voltage . We have considered iron alloy as work piece and copper is being used as tool with brine solution as electrolyte. Electrolyte is a mixture of NaCl and water. This breaks as:

$NaCl= Na++Cl-$ $\quad$ $H2O = H++OH-$

When voltage is applied between tool and workpiece negative ions move towards anode and positive ions move towards cathode. At cathode hydrogen ions take electrons from cathode (tool) and become hydrogen gas

$2H++2e- = H2$

At anode Fe2+ ions comes out of work piece and loses two electrons and combines with chloride ions to form ironchloride which remain in the solution as precipitate.

$$Fe = Fe+ + + 2e- \qquad Fe2+ + Cl- =FeCl2$$

Similarly hydroxyl ions combine with sodium ions and form sodium hydroxide.

$Na+ + OH- = NaOH$

Thus workpiece is machined and removed material is found as precipitate in electrolyte. Moreover there is nocoating on the tool, only hydrogen gas evolves at the tool or cathode.

ECM creates approximately the mirror image of tool on the workpiece. Advantages of ECM over other machining processes (e.g. turning and milling) include its applicability without any heat generation, residual stress, material hardness, no tool wear, comparably high material removal rate, smooth and bright surface, and production of components with complex geometry having stress-free and crack-free surfaces. So ECM finds application in many industrial productions including turbine blades, engine castings, bearing cages, gears, dies and molds and surgical implants. A recent study on technological and economical comparison of roughing operation of titanium and nickel based blisks by milling, EDM and ECM shows dependence on the geometry, ECM is comparable in machining titanium alloy. EDM is a better alternative for smaller batch sizes whereas ECM is more suitable for large scale production .The research and technological development activities in ECM and related hybrid processes continue to address its emerging applications.

Pulse electrochemical machining (PECM) is one of the variations of ECM in which a pulsed power supply is used instead of DC current. PECM gives higher machining accuracy, greater process stability and better suitability for control. These advantages will be due to the improved electrolyte flow in the inter-electrode gap, localization of anodic dissolution and small and stable gaps. When used for micromachining PECM is called as pulse electrochemical micromachining (PECMM). ECM process mechanism has been used with a pulse/pulse reverse approach to electro-polishing and thorough-mask electro-etching wich can be used for manufacturing automotive planetary gears, fluid control valves, medical stents and superconducting radio-frequency cavities. ECM applications include biomedical, deburring,, deep hole machining for automotive applications, aerospace and tribology.

Fig.1 Experimental setup of Electrochemical machine (patil & yadav-2013)

The process parameters like voltage, feed rate and current can be varied by using the control panel. The electrolyte NaCl is pumped from a tank lined with corrosion resistant coating with the help of corrosion resistant pump & is fed to the job.Spent electrolyte return to the tank and is reused. One of the major advantages of ECM is that multiple electrodes can be used on the same machining setup with excellent scalability. ECM using multiple electrodes used to machine arrays of micro holes resulted in increased productivity. Taper induced on the workpiece during ECM drilling is a major problem. Major tool designs for the reduction of taper include insulated tools, tools with shaped ends and dual pole tools .Tungsten micro tools coated with nickel showed

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more corrosion resistance and higher machining rates were observed .

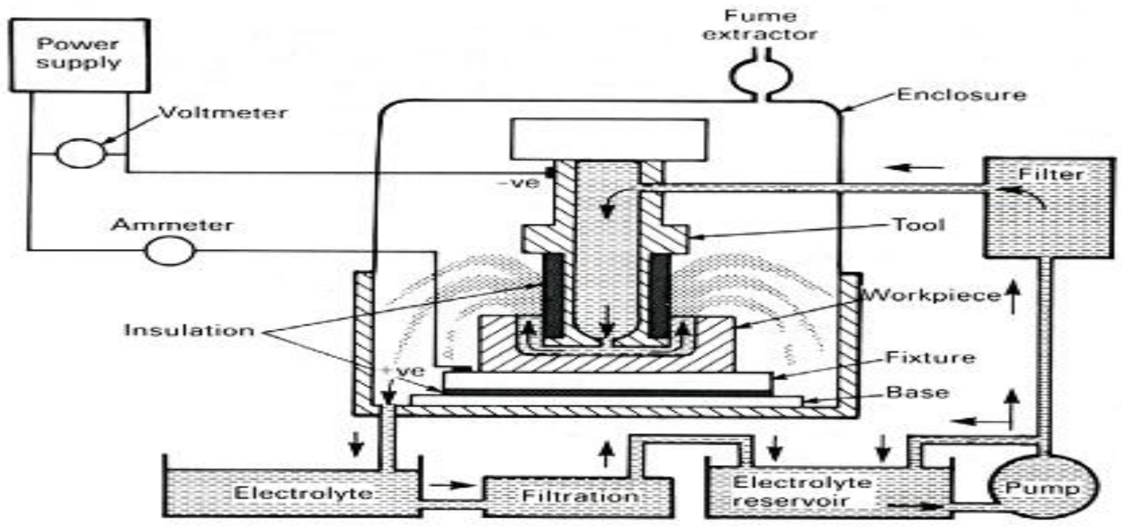

Fig.2 Schematic experimental set-up of ECM (source:pravin D.Babar(2013))

II. HISTORY OF ECM PROCESS

19th Century

Russian chemist E. Shpitalsky. offered in 1911, the process of electrolytic polishing which led to the origin of the electrochemical machining (ECM) as a technological method.

In 1928, Russian engineers V.N.Gusev and L.Rozhkov improved the technological ECM scheme by intensive flushing of electrolyte fluid through inter electrode space and moving (feeding) the EDM electrode with velocity equal to velocity of anode dissolution . Thus higher current density could be used which reduced the working inter electrode gap thus raised the target technological indicators of the ECM (quality of the surface ,accuracy and productivity).

In the "traditional" method of the electrochemical processing direct current was used along with continuous feed of the electrode and, as a rule, activating electrolyte fluids (homogenous salts of alkaline metals — KBr, KCl, NaCl etc.). Practical realization of such methods caused rather small working current density (10 … 40 A/cm ^{2}), and considerable inter electrode gaps (0.05 … 0.3 mm), not allowing to achieve competitive high accuracy of processing and quality of the surface.

In 1959 the Anocut Engineering Company, USA for the first time started the production of traditional model of the ECM using the direct current at the production run equipment.

In 1960-1970s bulk application of ECM in aerospace (industry), tool manufacturing (forging dies)
began in the USSR and Western Europe. Electrochemical technologies rapidly developed during
this period and well known firms as Mitsubishi, Hitachi, Philips, AEG Eloteherm, Amchem etc made the equipment.

In 80 – 90s more perfect schemes of impulse cyclic processing in passivating oxygen containing electrolyte fluids (water solutions of NaNO , KNO , NaClO , Na SO , etc.) were

Developed, which allowed to lower an error of processing to 0.02 … 0.06 mm and surface roughness to *R* 0.2 … 0.5 micron.

However, in connection with usage in hi-tech industries (aircraft engine building ,precision instruments industry, medical equipment and medicine, , etc.) complication of the form of parts and toughening of requirements to the quality of a facial layer, new groups of high duty and hard materials (including nanostructure materials), the necessity for new technologies in electrochemical processing has arisen. Result of this technical progress appeared in 1998 — 2011 in the form of whole complex of new bipolar microsecond ECM by vibrating electrode.

A special feature of these methods is that they are carried out at super small (2 … 10 micron) inter electrode gaps using high density impulse current (about 10^2 … 10 À/ cm^2).When performed at this level we can achieve small errors (0.001. 0.005 mm) of processing, creating parts of surfaces of regular macro and Micro reliefs with micron and submicron range, and obtaining optically smooth surfaces (*R* 0.1, 0.01 micron). All this is accompanied by higher (in comparison with competing technologies) productivity terms of finishing operations.

20th Century

Beginning of the 20th century saw the advent of researchers in Russia, Western Europe, and the USA using Various ways and techniques of ECM application for dimensional processing of parts mainly on operations of contouring and internal push broaching .

Recent developments

Shaped tube Electrochemical machining (STEM) process uses acidic electrolyte and is used in the drilling of cooling holes in turbines. ECM with electrolyte flow generated through extraction (reverse Of STEM) resulted in improved process stability and accuracy. Tool Vibrations with low frequency resulted in improved machining rate and accuracy due to the enhancement in the electrolyte flow conditions.

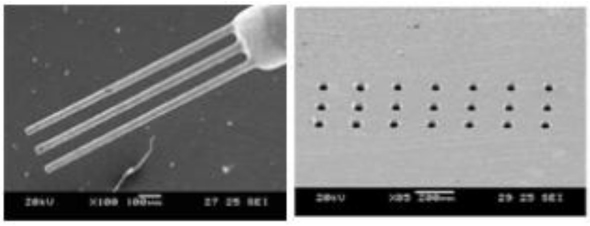

Fig.3 Microhole array fabricate during multiple electrodes (source:patil & yadav- 2013)

Jet electrochemical machining (JECM) is a new variation of ECM where the electrolyte is pumped in the form a jet through a nozzle . DC power is used between the workpiece and nozzle with the current being transferred by the jet of electrolyte. A flat electrolyte jet can be used to produce micro milled surfaces and electrochemical turning applications. The use of DC power contributes to higher machining rates when compared with pulsed ECM. Upto ± 5 µm accuracy and structures with aspect ratios of 3 can be machined using JECM Electrochemical machining using wire electrodes (WECM) can be compared to the wire EDM proces in many aspects . With the optimization of feed rate, vibration ,wire travel speed and electrolyte flow rate high precision microstructures with aspect ratio 30 can be produced. We can produce the wire electrode used in WECM in situ using ECM. Wires with diameters as small as 6 µm can be produced .

We can combine ECM with several other machining processes to improve the machining characteristics. A hybrid machining center consisting of electrochemical machining (ECM) electro discharge machining (EDM), and mechanical milling was developed . The hybrid process combined the advantages of each of the machining process to produce micro structures on difficult to machine carbides with low residual stress, high efficiency and low surface roughness (<100 nm). Ultrasonic vibration assisted electrochemical finishing process was studied and found to improve the surface finish when compared to regular electrochemical machining. The combination of ECM and EDM processes on the same setup is capable of generating highly complex and precise 3D structures . Deionised water which has the properties of a conductive fluid as well as a dielectric to some extent has been used to develop a process which involves simultaneous ECM and EDM . In Laser assisted ECM the area exposed to the electrolyte jet is targated with a laser beam focused on, which dissolves a specific region thus improving surface roughness and precision. This process also reports a higher MRR due to increased temperature in the region targeted by the laser beam. In abrasive ECM, the electrolyte contains abrasives like silicon carbide suspended freely in the vicinity of the work piece. These abrasives along with a wire cathode can be used for slicing silicon wafers with better production rate, good surface integrity and less cost. Electrochemical grinding is used to machine small holes with sharp edges. In this process the tool electrode is coated with abrasives and rotated at high speed. Initially material will be removed through the action of ECM and then the holes are ground for better finish through contact machining.

III. LITERATURE REVIEW

Klockea et al. (2015) analysed the basic research on the unpulsed electrochemical machinability of four typical γ-TiAl-based alloys. γ -TiAl-based alloys have attractive properties regarding the specific strength at high temperatures. Thus, the demand for such class of materials will increase significantly in aerospace industries . they investigated specific material removal rate as a function of current density and compared to the theoretical dissolution behaviour according to Faraday’s law. Finally observations on surface integrity aspects of these alloys are presented and compared to conventional cutting processes to show specific ECM process capabilities.they found that it is hard to machine γ-Titanium aluminates in terms of their electrochemical machinability . To analyze the machinability of several γ-TiAl the feed rate vs frontal gap width and surface roughness vs current density curves were examined. The experimentally determined material removal rates were compared to the theory according to Faraday’s law and to conventional titanium alloys.

Among the previously investigated titanium alloys the γ-TiAl have higher material removal rates. The amount of aluminium could be used for higher current efficiencies. Thus γ-TiAl, having approximately a five times higher amount of aluminium, possess higher material removal rates. moreover, all investigated materials have a good machining behaviour by ECM. Future work should focus on to improve the surface roughness such as PECM or a more homogenous dissolution characteristics of the different material phases. Furthermore the measured material removal rates should be assigning into a simulation model to observe the local gap forming of complex geometries like turbine blades. With the use of this simulation model future tool designing technique can be made more efficient and accurate.

K.P. Rajurkar et al.(2013) discussed about ECM process modeling,simulation and tool design as in ECM and its variant processes which is essential to evaluate the anode material removal thickness at a given time increment. The material removal thickness is a function of current density variation at the gap on altering electrical conductivity of the electrolyte. The electrolyte properties varies with the temperature and gas bubble formation, which further depend on the velocity and pressure fields apart from current density. Therefore ECM modeling consist of a set of mass, heat electric charge transfer equations, Simulation of the heat generated during the ECM process and its efficient dissipation using electrolytic flow is important. It was found that a hollow cathode and pulse voltages help in the effective control of the heat generated. As ECM process parameters and it's control are still now dependent on the human operators' experience,thus expert systems automating the process are needed. Some examples of expert systems currently implemented comprise of artificial neural networks and fuzzy logic controls.They also discussed about Micro ECM monitoring based on voltage and current feedback signals from oscilloscopes or current sensors. The waveform observed on the oscilloscope can be used to predict the MRR, hole accuracy and machining time. They also discussed about the process capability of ECM which ranges from wide variety of conductive, hard to machine, engineering materials like metals, semiconductors **as well as** composites**.** Features as small as 0.5 µm can be machined using ECM. A study of ECM generated surface behavior of titanium revealed that higher rates of electrolyte flow resulted in improvement of material removal rate and better surface finish. Holes with complex internal structures and undercuts can be machined using ECM that are otherwise almost impossible to be machined using any other process. The non-contact nature of ECM enables the drilling holes having an inclinationof40ºusing wedge shape electrodes. They also discussed about Acidic, basic and neutral aqueous solutions used as electrolyte in ECM. Dilute acidic solutions are preferred for ECM of steel and it's alloys due to the solubility of the metal debris in to the electrolyte**.**

XiaolongFang et al.(2013) studied the Effects of pulsating electrolyte flow in ECM.They attempted to generate the pulsating flow by a servo-valve in the electrolytic supply pipe, which is introduced to improve the heat transfer, material removal rate and surface profile.They also presented a multi-physics model coupling of electric, heat, transport of diluted species and fluid flow.Simulation results indicate that pulsating flow has significant impact on the distributions velocity,gasfraction,andtemperatureneartheworkpiecesurfacealongtheflowdirection.They conducted experiments conducted to verify the feasibility of the proposed process and study effects of pulsating flow on material removal rate.They found that as the pulsating amplitude increases, the relative material removal rate first increases and then decreases.

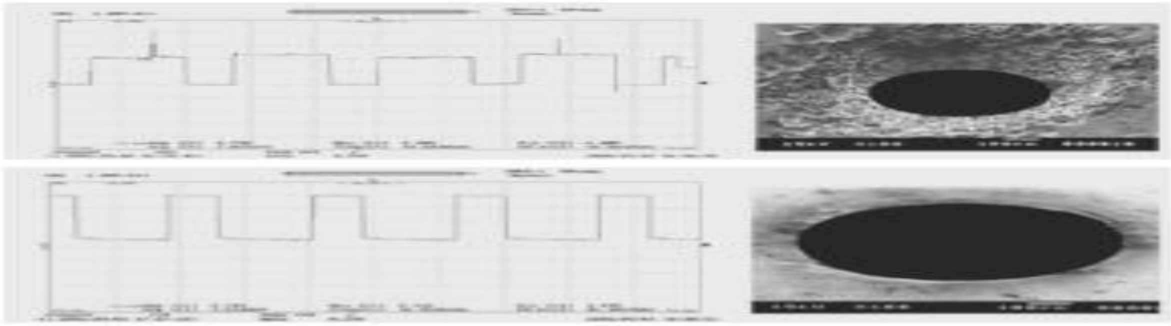

Fig.4 Waveforms of Top Spark affected hole; (Bottom) No spark affect hole{source:K.P Rajurkar at el.(2013)}

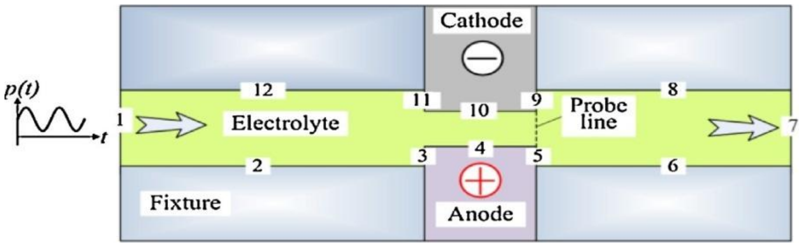

Fig.5 Schematic diagram of ECM with pulsating electrolyte flow

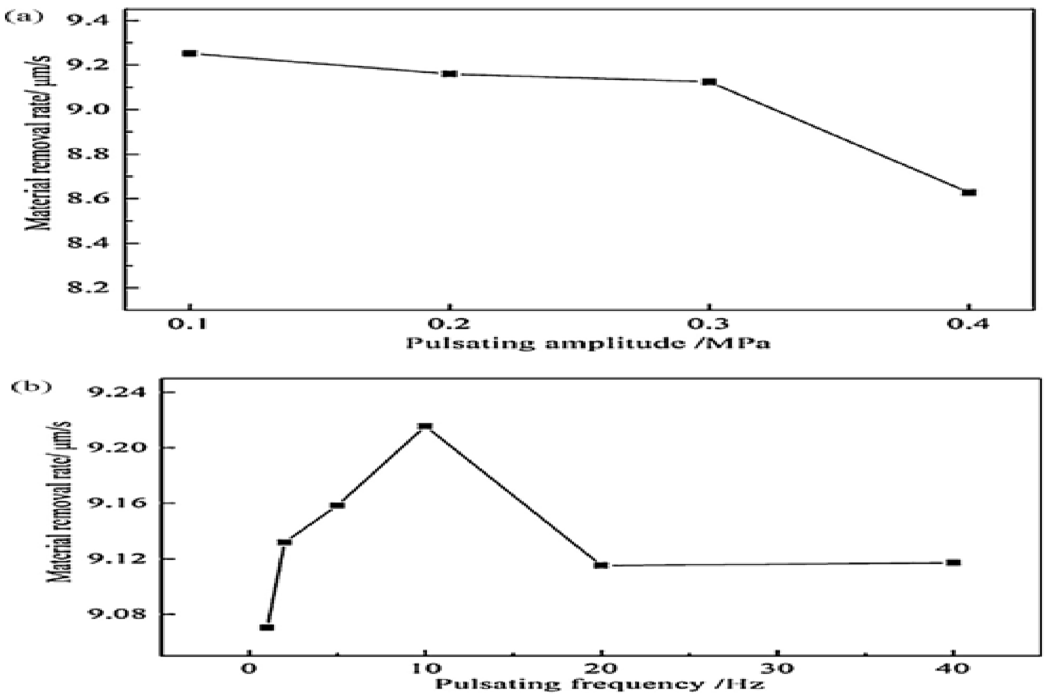

Fig.6 variation of MRR with pulsating frequency(source: XiaolongFang et al.-(2013)

It was also observed that as the pulsating frequency increases, the relative material removal rate obtained from the experiments first increases and then decreases.

Pravin D.Babar and Baliram R.Jadhav (2013) investigates the effect and parametric optimization of Titanium alloy by ECM. The process parameters considered for optimization are concentration of electrolyte , applied voltage and feed rate in consideration of material removal rate . Analysis of variance is performed to get contribution of each parameter on the performance characteristics and it was observed that feed rate is the most significant process variable and then the Feed rate and concentration of NaCl, that affects the ECM robustness . S. Qu et al.(2013) investigated about the Enhancement of surface roughness of Ti6Al4V by pulsating electrolyte. The better surface outline and optimized MRR could be obtained with the help of pulse electrolyte in direct current ECM . For ECM with pulsating the significant process parameter electrolyte are pulsating electrolyte flow frequency and amplitude. The pulsating electrolyte is similarly beneficial in improving the machined surface roughness and MRR when the proper pulsating electrolyte flow frequency and amplitude are used. However, the effects of pulsating flow on pulsed current the direct current ECM is most efficient in comparison to pulse current ECM . When a constant voltage is applied , the difference in electrolyte conductivity and potential in the inter-electrode gap is smaller, which may lead to a more homogeneous machined surface outline . It has been observed that the surface texture decreases as the electric potential voltage increases. It should be observed that the lowest surface texture is observed when the MRR is highest in these direct current ECM experiments. ECM with pulsating electrolyte is a promising topic in the enhancement of surface roughness.

Pratapsingh Patil et al.(2013) evaluated material removal rate using circular-shaped tube Electrode In Electrochemical Machining. They attempted to find out the feasibility of making drilled hole using circular-shaped tube copper electrode in ECM. The material was used as a workpiece is stainless steel and the process variable selected for study were diameter of electrode ,conductivity of electrolyte and applied voltage with Taguchi design approach.

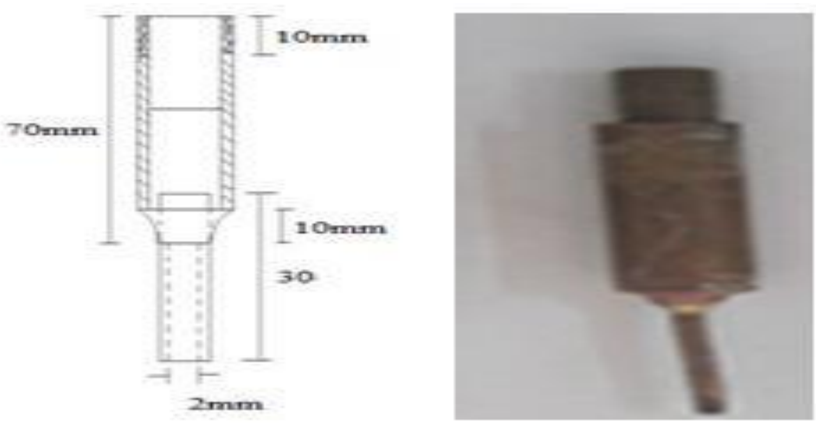

Fig.7 circular- shaped tube copper electrode(source: Patil et al.-2013)

copper was taken as electrode material and designed in circular shape so as to cut the cavity in stainless steel in the similar profile. The ECM tooling is approximately the reflection of the machined section of the machined part. The Taguchi technique is based on statistical design of experiments and is applied at the process draft stage to create ideal process settings or design parameters. Statistically designed investigation based on Taguchi methods were accomplished using L9 orthogonal arrays to analyze the material removal rate as process variable,theoretical ANOVA and S/N ratio constitute for data analysis drew similar conclusions. Statistical conclusions give the voltage , feed rate ,electrode diameter and electrolyte conductivity which affects the MRR by 25.84%, 37.55% , 25.19 % and 11.40 % in the electrochemical machining of SS- 304L, respectively.

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Thanigaivelaet al.(2012) discussed the effect of process parameter such as electrolyte concentration, machining voltage, frequency, and duty cycle on the material removal rate and overcut were studied using copper workpiece. L18 orthogonal array is used as per taguchi quality design concept. ANOVA is also performed to determine the most significant parameter that influences the EMM(electrochemical micromachining) process. The optimum process parameters for lower overcut and higher MRR are found out and confirmation tests establised validation of the prediction. The confirmation test results showed 19% and 20.78 % improvements of overcut and MRR respectively with respect to the initial parametric setting. Confirmation tests resulted in improvements of the overcut and MRR to the optimal machining of about 20.78% and 19% respectively. The most significant parameters based on the F value that influenced the overcut and MRR are found to be frequency and electrolyte concentration respectively. Micro-holes were machined using the indigeneously developed EMM setup and analysed using Taguchi's method of DOE. Process parameters like voltage, , duty cycle, frequency and electrolyte concentrationand were varied according to L18 orthogonal array. Based on the S/N ratio and analysis of variance (ANOVA).Uttarwar and Chopade(2009) **i**nvestigat**e** the effect of voltage variation on MRR for Stainless steel EN Series 58A (AISI302B). With gradual increase in voltage MRR increases keeping IEG (Inter Electrode gap) variable maintained constant during the whole procedure. The machining voltage 45V (0.33A) gives the appreciable amount of MRR. By considering other process parameters, the said procedure can be continued to find results at their optimum values. Secondly the difference between the values of theoretical MRR and Practical MRR are also required to give ideas so that large percentage error can be reduced.

S.K.Mukherjee, S.Kumar et al.(2008)studied the effect of valency on material removal rate in electrochemical machining of aluminium. Material removal rate (MRR) of aluminium work piece has been obtained by electrochemical machining using NaCl electrolyte at various current densities and compared with the theoretical values. Rapid feed rate is highly productive and produces the good quality of surface finish. However,removal of hydrogen gas and product of machining limits the feed rate. Using increased value of the penetration rate equilibrium machining gap decreases and it becomes more difficult to flow the electrolyte effectively. Under such conditions, short circuiting of electrodes leads to spark which damage the workpiece and the tool. Another boundation for using higher feed rate is that fine filtering commensurate is required along with reduced equilibrium machining gap.

Silva et al.(2006) studied intervening variables in electrochemical machining. The roughness, over-cut and material removal rate (MRR) were studied. Four parameters were varied during the experiments: electrolyte, voltage ,feed rate and flow rate of the electrolyte Forty-eight experiments were conducted out in the equipment developed.Two electrolytic solutions were used: sodium nitrate ($NaNO_3$) and sodium chloride (NaCl) . The results show that feedrate was the main parameter affecting the material removal rate.The electrochemical machining with sodium nitride yielded the best results of surface roughness and over-cut.

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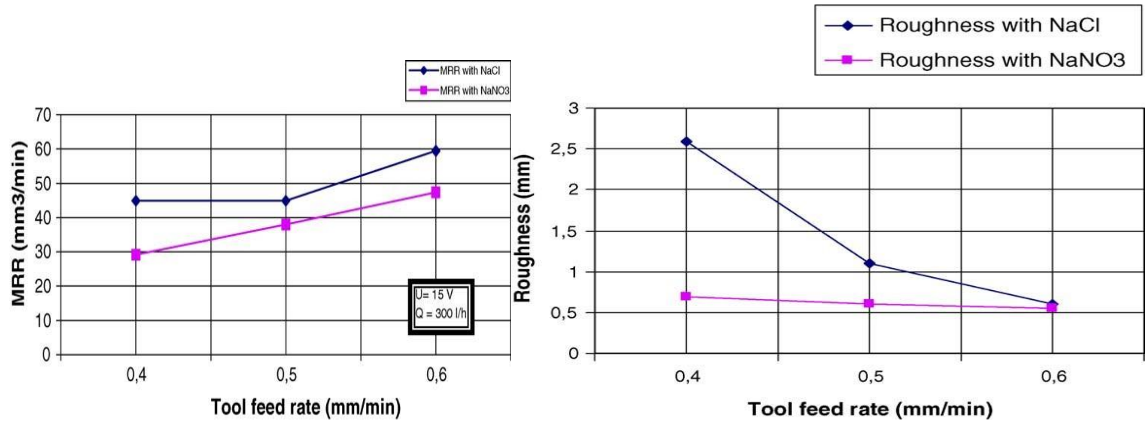

Fig.8 variation of MRR(mm3/min) with tool feed rate(mm/min) (source: Silva et al.-2006)

According to the results mentioned in this work main conclusions are:

a. Surface roughness decreases with feedrate.

b. The MRR was affected by tool feedrate.

c. The $NaNO_3$electrolyte resulted in lower surface roughness and over-cut than NaCl.

d. Irregular removal of material is more likely to occur at low feedrates.

S. K. Mukherjee et al.(2005) studied the Effect of Over Voltage on Material Removal Rate during ECM.It is observed that over voltage is very sensitive to tool feed rate and equilibrium gap. Material removal rate decreases due to decrease in current efficiency and increase in over voltage, which is directly related to the conductivity of the electrolyte solution. The actual current density was always greater than the corrected current density. The over-voltage is the important parameters which restrict the material removal rate and is sensitive to tool feed rate and equilibrium machining gap. The effect of penetration rate on machining gap and current density is given in table.

IV.CONCLUSION

From the above discussions, it is evident that historical developments have led to the improvements in surface finish and material removal rate on account of latest technological developments. Application of the Taguchi method for optimization of process parameters which are selected taking into account of the manufacturer and industrial requirements. Selection of an orthogonal array-L6, L9,L27 etc., using conceptual signal-to-noise (S/N) ratio approach, analysis of variance (ANOVA), MINITAB software has to be carried out .Therefore, the control of process parameters can improve surface roughness, material removal rate, microstructure, operating, maintenance, tooling, cost for specific industrial applications as per specified design requirements.

V. FUTURE INVESTIGATION

Authors propose to study the effect of input parameters i.e. feed rate, voltage, flow rate of electrolyte, current density, electrolyte concentration , electrode diameter etc. on output characteristics i.e. geometry, material removal rate , strength, microstructure, and of stainless steel plates of various grades e.g. AISI 202,AISI 304 etc. Ti6Al4V by ECM machine Model EC MAC-II by using electrodes of different shapes and measurement of MRR and analysis using DOE, Taguchi method, ANOVA analysis, MINITAB software and S/N ratio approach may be applied for the optimization of output parametersfor the best performance in specific application.

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