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Influence of pulse period and duty ratio on electrochemical micro machining (EMM) characteristics

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Abstract: Electrochemical Micro Machining (EMM) appears to be promising as a future micro machining technique since in many areas of applications; it offers several advantages including electronic, biomedical and MEMS/NEMS applications. Electrochemical Machining (ECM) can be effectively used in the micron range by maintaining very smaller inter electrode gap with proper controlling of predominant micromachining parameters during machining. Present paper will highlight the influence of various EMM process parameters i.e. machining voltage, electrolyte concentration, pulse period and duty cycle ratio on machining performance criteria e.g. material removal rate and machining accuracy to meet the micro machining requirements. Some of the experiments had been carried out on copper to investigate the most effective zone, which gives high machining accuracy with appreciable amount of material removal rate and optimum machining speed. From the experimental results, it has been observed that the introduction of short pulse period improves EMM performance characteristics. Attempt has also been made to study and compare the surface condition of the machined micro holes through SEM micrographs. From the analysis of test results and SEM micrographs it can be observed that optimum value of machining voltage is about 3V, pulse period is about 200 μsec, duty cycle ratio is about 20% and electrolyte concentration is about 20 g/l which will produce accurate micro holes with highest possible amount of material removal.

Keywords: EMM, Short Pulse, Machining Speed, Unit Removal

1. Introduction

In un-conventional machining processes, Electrochemical machining (ECM) has tremendous potential on account of versatility of its applications and it is expected that it will be one of the promising, successful and commercially utilized machining processes in the modern manufacturing industries. The ECM process was first patented by Gusseff in 1929. Significant advances during the 1950s and 1960s developed ECM into a major machining technology in the aircraft and aerospace industries for shaping, finishing, deburring and milling operations of large parts [McGough J A, 1974; Rajurkar K P et al 1999]. All these processes of ECM now play an important role in the manufacturing of a variety of parts ranging from machining of complicated, shaped large metallic pieces to opening of windows in silicon that are a few microns in diameter. ECM has seen a resurgence of industrial interest in the last decade due to its various advantages over other machining process such as no tool wear, stress/burr free, high MRR, bright surface finish and the ability to machine complex shapes in materials regardless of their hardness. ECM is an anodic atomic-dissolution process where work piece and tool are respectively anode and cathode, which are separated by an electrolyte. When electric current is passed through the electrolyte the anode workpiece dissolves locally so that the shape of generated workpiece is approximately negative mirror image of the tool. Electrolyte, which is generally a concentrated salt solution, is pumped at high velocities through the machining gap in order to remove reaction products and to dissipate heat generated without affecting stability of the tool.

Micro machining refers to small amount of material removal that ranges from 1 to 999 μm. However material removal should take place <500 μm for effective micro machining. Micro machining is the most basic technology of the manufacture of miniaturized parts and components [Masuzawa T, 2000]. Miniaturization will continue as long as people require compact and better quality products. The machining of materials on micrometer and sub micrometer scales is considered to be a key of future technology. Electrochemical machining process is applied to micro range of applications for the production of miniaturized parts with high precision; it is called Electrochemical Micro Machining (EMM). EMM is an effective method of producing variety of micro components for the aerospace, automotive, defense, electronic and biomedical industries. Fig.1 shows the outline view of a developed electrochemical micro machining (EMM) system set up. A better understanding of the high rate dissolution is urgently required for EMM to become widely employed manufacturing process in the micro-manufacturing domain. Although research institutes have already initiated some research work in this area of micro machining, it still requires lot. For fulfilling various research objectives and needs of EMM in the area of micro machining, the present research highlights the development of EMM system considering the influence of machining parameters like machining voltage, pulse period and pulse duty ratio on material removal rate, machining accuracy and machining speed.

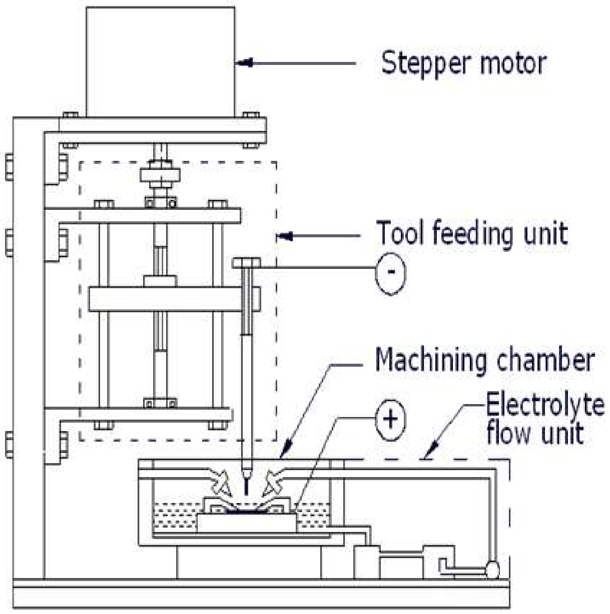


Fig.1. *Outline view of electrochemical micro machining (EMM) system set up.*

2. Importance of EMM

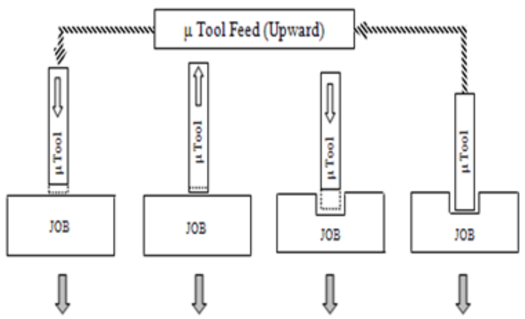
Recent changes in societies demand have forced us to introduce more and more micro parts with high accuracy into various parts of industrial products. For example the fuel injection nozzle for automobiles, several regulations arising from environmental problems have forced us to improve the design of the nozzles towards those of smaller, compact with high accuracy. Palm-tops, mobiles, mini robots for diagnostic etc are the examples for the miniaturization. Inspection of internal organs of a human body and surgery without pain are universally desired. Metallic body-inserts must be micro-machined meticulously for use in bone surgery i.e. pins, plates and artificial joints in order to support body compatibility.

Conventional processes can also be used in micro manufacturing area, but the problems generally faced are tool wear, rigidity of the tool and heat generation at the tool work piece interface. Sometimes, it is difficulty to produce complex shapes [Masuzawa T, 1997]. So far, Un-conventional machining processes like Electrochemical machining (ECM), Electro discharge machining (EDM), Laser beam machining (LBM), Electron beam machining (EBM), Chemical machining (CM) etc. have been utilized for ultra precision machining. Most of the machining processes (EDM, LBM and EBM etc) are thermal oriented processes, therefore it causes the formation of heat-affected zones (HAZ) and micro cracks on the work piece [Bhattacharyya B et al, 2004]. Chemical machining (CM) and Electrochemical machining are thermal free but CM is slow process and cannot be applied on chemically resistant materials like titanium, copper alloys, stainless steel and super alloys, which are widely used in bio-medical, electronic and MEMS/NEMS applications [Landolt D et al, 2003; Bhattacharyya B et al, 2002]. Sometimes, chemical machining may not be controlled properly in micro machining zone. ECM technique does not produce thermal or mechanical stresses, micro cracks on the work piece material and moreover, it can be applied all types of chemically resistive electrically conductive materials. In many areas of applications EMM offers several advantages over other micro machining processes that include high MRR, higher accuracy, high speed etc. Therefore EMM appears to be very promising micro machining technique in nearby future.

3. EMM System

Considering the influence of predominant process characteristics, a well-planned research program has been considered for experimentation in the developed EMM system [8]. The developed system consists of various sub-components, e.g. mechanical machining unit, electrical power and controlling system, and controlled electrolyte flow system, etc. The mechanical machining unit comprises of systematic mechanical arrangement for providing feed to the micro tool i.e. 2.4 μm/sec and also machining chamber, which is placed below the tool holder unit. Electrical power and controlling system consists of high frequency DC pulse generator, micro tool feed control unit and Inter Electrode Gap (IEG) control unit. High frequency DC pulse generator supplies the required power i.e. short pulses with different duty ratios for micro machining. Micro tool feed control unit is used to control the micro tool feed rate with the help of stepper motor interfaced with pre-programmed Intel 8085 microprocessor. Microprocessor is programmed in such a way that stepper motor rotates three steps clockwise followed by two steps counter clockwise and the resultant rotation is one step clockwise. This will help to create forward and backward movements to the micro tool leading to resultant tool feed during micromachining operation and facilitate effective sludge removal from the narrow machining gap. The fresh electrolyte is directed through the nozzles to the machining zone with a pressure without affecting the stability of the micro tool and intern the shape.

For Micromachining, the IEG should be around 20 µm for effective machining with higher capabilities [Kozak J et al, 2004]. Fig.2 shows the IEG control strategy and sequence of operations for maintaining narrow end gap. First, a sensing voltage i.e. 0.5 – 1V, which is smaller than the machining voltage, is applied between micro tool and the workpiece in absence of electrolyte, and monitored through ammeter. Initially micro tool moves downward direction, if contact occurs, no gap condition the micro tool is moved upward direction with the help of stepper motor and set the required IEG i.e. 20 µm. High frequency pulsed power supply is applied for micro machining for improving the machining accuracy [Ahn S H et al, 2004]. Machining voltage i.e. 3V, 5V, 7V and 9V is applied between micro tool and workpiece for machining in the presence of electrolyte. Now the micro tool starts moving downward direction for machining with the help of microprocessor through stepper motor. The micro tool feed rate (downward motion) must be lower than unit removal for effective machining. If not, micro tool about to touch the workpiece and cause for short current, which in turn cut-off the power supply. After short current micro tool moves in upward direction and continues the same sequence of operation for proper control of inter electrode gap.



Voltage	Sensing voltage i.e. 0.5 – 1V	No voltage	Machining Voltage i.e. 3 - 9V	Machining Voltage i.e. 3 - 9V
Tool movement	Downward	Upward	Downward	Downward
Remarks	Ammeter	Set proper IEG i.e. 20 µm	Maintain proper flushing of electrolyte	Short-current i.e. IEG Controller

Fig.2. *Control sequence of IEG.*

The machining accuracy of the workpiece as well as process stability is decided by setting, maintaining and controlling the main process parameters in the IEG. Some of the EMM process parameters/variables that affect the machining accuracy are shown in Fig. 3 as cause and effect (fish-bone) diagram, which has to be addressed. For achieving higher machining accuracy, selection of optimal variables plays a vital role. These variables have to be considered while designing the experimentation as well as setup. Apart from this, experiments have to be carried out to find the optimal combination of process parameters for achieving higher machining accuracy.

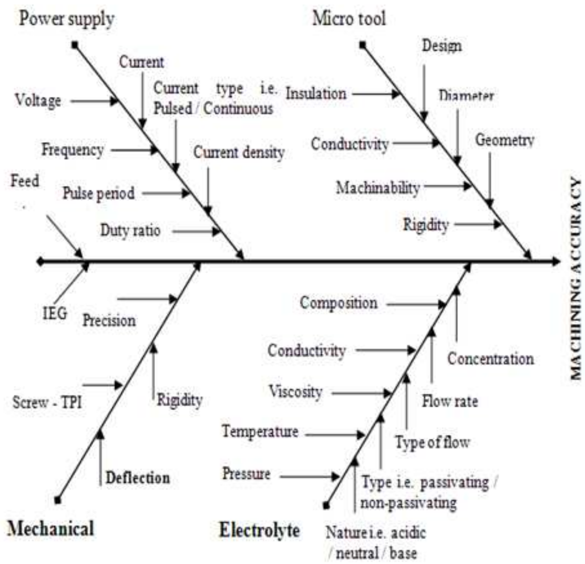


Fig. 3. *Cause and effect (fish-bone) diagram.*

4. Experimental Planning

To analyze the influence of predominant process parameters during EMM operation on the desired performance characteristic i.e. material removal and machining accuracy, proper scheme has been designed with the utilization of developed EMM experimental set up with high frequency pulse generating unit. Pulsed current improves the surface quality and accuracy of the machined part. High frequency pulse generator is capable of supplying ultra short pulses, which can improve the micro machining capabilities. Micro tool of Φ 260 -µm stainless steel has been chosen for the experimentation. The work piece specimens were 15mm X 10mm X 0.15 mm mask-less copper plates. The electrolyte used for experimentation was fresh aqueous sodium nitrate ($NaNO_3$) having concentration of 10 g/l, 20 g/l and 30 g/l. Variable rectangular DC pulsed supply in the range of microsecond pulse period was used for experimentation. The material removal rate (MRR) and accuracy had been observed for various sets of experiments with different combinations of process parameters. Micro tool feed rate was maintained as low as possible i.e. 2.4 µm/sec through control unit, which is most appropriate value for the existing EMM set up that can enhance the micromachining accuracy. Pulsed power supply of 80% duty ratio is selected in order to achieve higher MRR for the first phase experiments. Pulse on: off ratio is considered in the form of duty cycle ratio or duty ratio. Duty ratio is defined as

$$Dutyratio = \frac{T_{on}}{T_{on} + T_{off}} \quad (1)$$

Where T_{on}: Pulse on-time and T_{off}: Pulse off-time

Unit Removal (UR) is defined as material removal per unit pulse or unit time. Material removal per unit time i.e. MRR is considered as UR for the experiments. Machining voltage of 3V, 5V, 7V and 9V were selected and micro second pulse period i.e. 200 µsec, 2000 µsec and 20000 µsec were chosen for experimentation. By selecting micro second pulses, stray current affected area can be reduced during machining. Duty ratio of 20%, 40%, 60% and 80% were selected for the second phase of experimentation. Machining accuracy was measured interns of side gap phenomena. Side gap is the average difference between the micro hole radius to that of micro tool radius. Micro hole inspection and measurement were performed with the help of measuring microscope (Olympus, Japan) and the side gap of the machined micro holes was calculated. Pulse nature is monitored through digital storage oscilloscope (DL 750 Yokogawa, Japan) during machining. Material weight was measured before and after machining by using precision weighing machine (Mettler Toledo, Switzerland) and machining time was noted with help of stopwatch (Baker, India) for calculating unit removal intern of material removal rate.

Machining speed is calculated as

$$\text{Machining speed} = \frac{\text{Distance travelled by the micro tool during dissolution}}{\text{Micro tool penetration time}} \quad (2)$$

For studying the effects of various predominant process parameters i.e. electrolyte concentration, machining voltage, micro second pulse period and duty ratio on accuracy, micro machined holes had been viewed through scanning electron microscope (SEM) (Joel, Japan) and SEM micrographs were further analyzed.

5. Experimental Results and Discussions

Experiments had been carried out in different phases on the developed EMM experimental set up with various process parameters to predict the influence on unit removal (UR), machining accuracy and machining speed. In the initial phase of experimentation, experiments were carried out with different electrolyte concentrations i.e. 10 g/l, 20 g/l and 30 g/l, and from the analysis of test results it has been observed that highest accuracy with optimum unit removal (UR) is achievable at 20 g/l electrolyte concentration, which had corroborated our previous work [Bhattacharyya B et al, 2005] So, first and second phase of experiments were restricted to 20 g/l electrolyte concentration. In first phase, machining voltage and pulse period effects were studied and in the second phase, pulse period and duty ratio influences were considered.

5.1. Influence of Machining Voltage and Pulse Period on Unit Removal, Machining Accuracy and Machining Speed

In the first phase, experiments were conducted on the EMM experimental setup with various process parameters to predict the influence of micro second pulse period and machining voltage. Experimental results were depicted in the form of graphs to exhibit the influence of the micro second pulse period and machining voltage on unit removal, machining accuracy and machining speed. An attempt has been made to find out an optimal combination of machining parameters for effective and efficient micromachining.

5.1.1. Variation of Unit Removal with Machining Voltage for Different Pulse Period

Fig. 4 shows the effect of machining voltage on UR at different pulse period i.e. 200 µsec, 2000 µsec and 20000 µsec at 20 g/l electrolyte concentration and 80% duty cycle ratio. The graph shows higher UR at higher machining voltage as well as larger pulse period. At higher machining voltage machining current increases, which in turn increase the current density that causes more machining reactions to occur and leads to higher UR. At larger pulse period, the machining current is more and it causes higher dissolution according to Faraday's law that results higher UR. From figure, it can be observed that UR is increasing linearly with larger pulse period for all machining voltages except 20000 micro sec at 5V. At 5V, 20000 micro sec, UR is slightly lower may be due to formation of salty layers over the machining zone that disrupts the dissolution process, occurrence of shortcomings like voltage variation in IEG, improper flow of electrolyte and other mechanical constraints during machining.

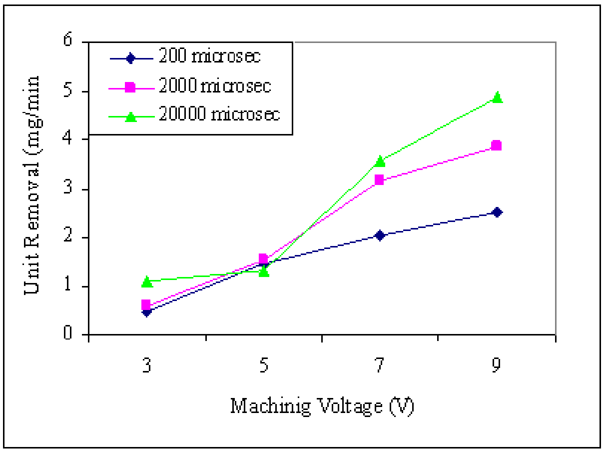


Fig .4. *Machining Voltage Vs UR at 20 g/l for different pulse period.*

5.1.2. Variation of Side Gap with Machining Voltage for Different Pulse Period

Fig. 5 exhibits the machining voltage effect on side gap at different pulse period as stated in the previous set of experiments. From figure, it can be noted that side gap is increasing with machining voltage and pulse period except for 2000 µsec curve at 7V. Increase in machining voltage causes varying local electrolyte conductivity due to joule heat generation in IEG at higher current density that reduces the localization effect of current, and stray current flow increases, which intern cause more lateral removal of the material from larger surface area of the workpiece and results more side gap. By reducing the voltage and maintaining small IEG, current flux density would be focused more in linear direction (along the tool i.e. Z-direction) and almost negligible in lateral direction (across the tool) that reduces the removal of material from larger surface area of the workpiece intern causes less side gap. Due to larger pulse period, the on-time pulse duration is more than off-time, so the reaction products during machining cannot be removed properly within the short span of off-time and these reaction products disrupts the dissolution process and in sometimes cause micro sparking that leads to more side gap. The effect of stray current is also predominant due to higher pulse period, which can be reduced by short pulses. At short pulse period, the on-time of the machining current is limited for dissolution. So the reaction products i.e. sludge, gas bubbles are less and these products are flushed away completely from the narrow machining zone by flowing electrolyte during off-time. By maintaining cleaned environment around the IEG zone, the machining current fluxes are focused linearly towards the workpiece, which intern reduces the effect of stray current. Shorter pulse also improves heat dissipation within the IEG. Machining resolution is limited to a few microns by applying short pulses. Pulse period of 2000 µsec curve shows little lower side gap at 7V due to localized generation of micro sparks during machining.

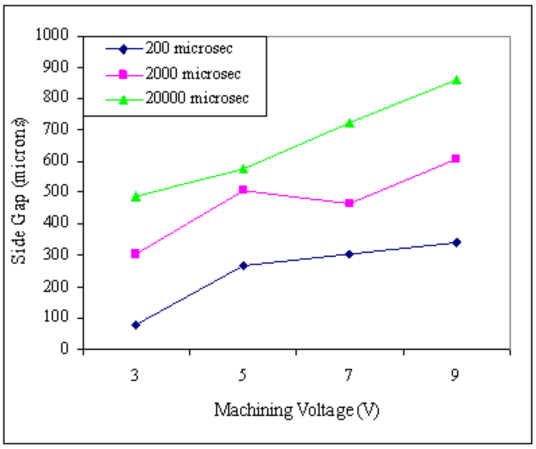


Fig.5. *Machining Voltage Vs Side Gap at 20 g/l for different pulse period.*

5.1.3. Variation of Machining Speed with Machining Voltage for Different Pulse Period

From Fig.6 it can be observed that machining speed is increasing with machining voltage and pulse period. At higher machining voltage, current density is more that can improve dissolution rate. At higher pulse period; pulse on-time is more, which improves the unit removal. By maintaining proper IEG, the current flux density in the IEG is higher than its surrounding gap i.e. lateral side. So anodic dissolution becomes more localized, which intern improves the machining speed. In 2000 µsec pulse period curve shows higher machining speed at 7V condition due to localized generation of micro sparks during machining.

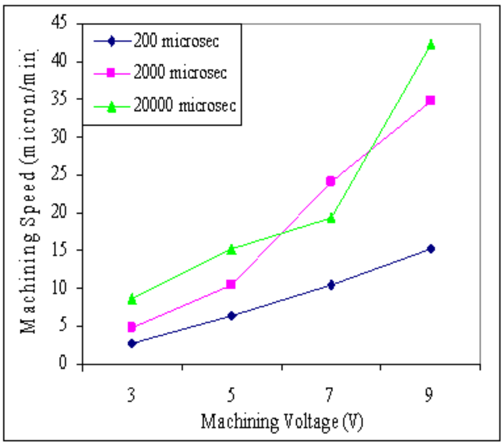


Fig.6. *Machining Voltage Vs Machining Speed at 20 g/l for different pulse period.*

5.1.4. Analysis of SEM Micrographs and Voltage Graphs

Fig.7 shows the SEM micrograph of machined micro hole at 20 g/l electrolyte concentration, 3V machining voltage and 200 µsec pulse period. From the figure, it can be observed that the machining accuracy and surface integrity is good, and moreover stray current effect is restricted. Shorter pulse localizes the anodic dissolution process and results lesser side gap. Using short pulses, the average off-time pulse duration is increased, so the reaction products during machining can be removed effectively, which intern reduces the side gap and leads to higher accuracy and surface integrity. Better accuracy and surface quality can be achieved by using shorter pulses. Fig.8 also shows the SEM micrograph of machined micro hole at the same above-mentioned parametric condition, but at different pulse period. From Fig.8, effect of micro sparks can be observed clearly and also the generated periphery of the machined micro hole is not good due to higher pulse period. At higher pulse period i.e. 2000 µsec, on-time is more so the dissolution rate increases and these dissolved products cannot be removed properly within short span of off-time that causes uneven machining and reduces the accuracy and surface integrity. Moreover, it also causes varying local electrolyte conductivity due to Joule heat generation in IEG that reduces the linear dissolution and subsequently increases the lateral dissolution, which results unevenness and more side gap. Fig.9 shows the voltage graph of pulse nature captured through digital storage oscilloscope during micro machining at 3V and 200 µsec. From figure, it can be noted that pulse nature is good due to effective and efficient micro machining at this parametric condition, and it also supports the previous conclusion, which has been derived from the analysis of micrographs. During experimentation, pulse nature is monitored through digital storage oscilloscope and subsequently micro machining is controlled with IEG control unit through short current.

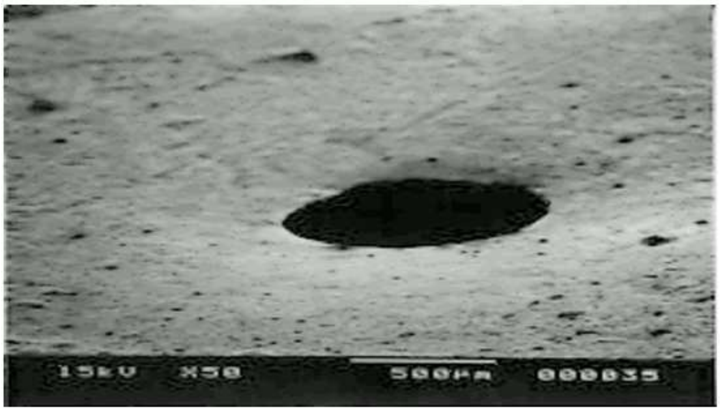


Fig.7. *SEM Micrograph of machined micro hole (20 g/l elect. conc., 3V m/c voltage and 200 μsec pulse period).*

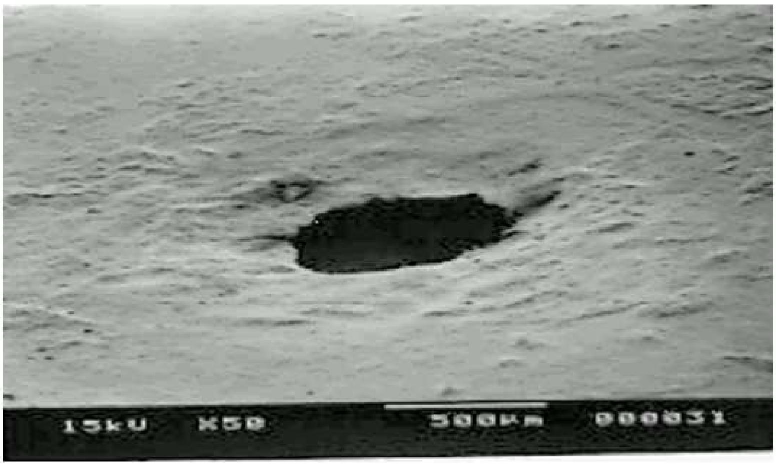


Fig.8. *SEM Micrograph of machined micro hole (20 g/l elect. conc., 3V m/c voltage and 2000 μsec pulse period).*

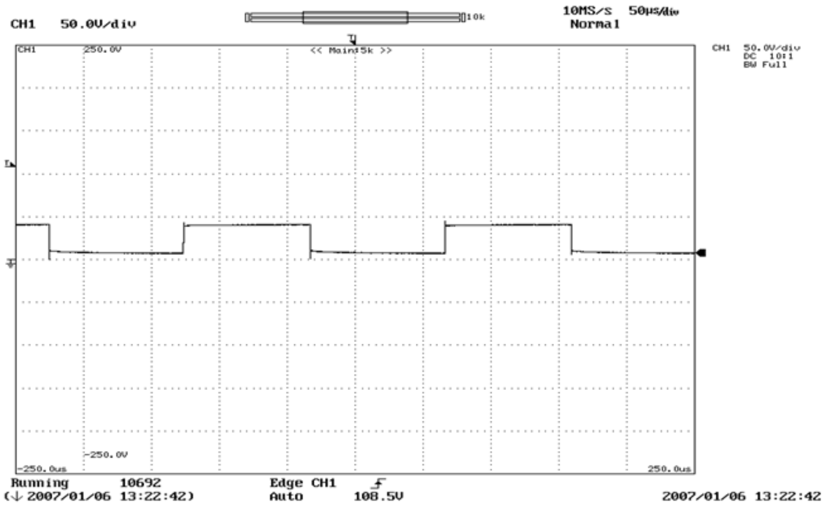


Fig.9. *Voltage graph of pulse nature during machining (3V m/c voltage and 200 μsec pulse period).*

5.2. Influence of Pulse Period and Duty Ratio on UR and Machining Accuracy

From the analysis of first phase experimental results, it has been concluded that highest accuracy with optimal unit removal and machining speed was attained at 3 V machining voltage and 200 μsec pulse period. So, the second phase of experimentation was carried out at 20 g/l electrolyte concentration and 3 V machining voltage. Experiments were carried out and the results were plotted in the form of graphs to exhibit the influence of the micro second pulse period and duty ratio on UR and machining accuracy. Since machining speed is dependent on UR, it was not plotted separately. An attempt has also been initiated to find out an optimal combination of machining parameters.

5.2.1. Variation of Unit Removal with Pulse Period for Different Duty Ratio

Figure 10 shows the effect of micro second pulse period on unit removal at different duty ratio's i.e. 20%, 40%, 60% and 80%. From figure it can be noted that unit removal is increasing with microsecond pulse period except for 2000 µsec curve at 60% and 80% duty ratio. Higher pulse period increases the pulse on-time that leads to higher dissolution according to Faraday's law and it finally tends towards higher unit removal (UR). But 2000 µsec curve shows lower unit removal at 60% and 80% duty ratio may be due to formation of passive anodic layers over the machining zone, improper flushing of electrolyte that makes accumulation of sludge and other reaction products, which disturbs the dissolution process. At 40% duty ratio, highest unit removal can be observed in all pulse period conditions. At this ratio, pulse on-time is less than pulse off-time. During on-time, electrochemical dissolution of anode takes place and during off-time these dissolved reaction products were flushed away completely from the machining zone and keeps the machining zone ready for next phase of dissolution.

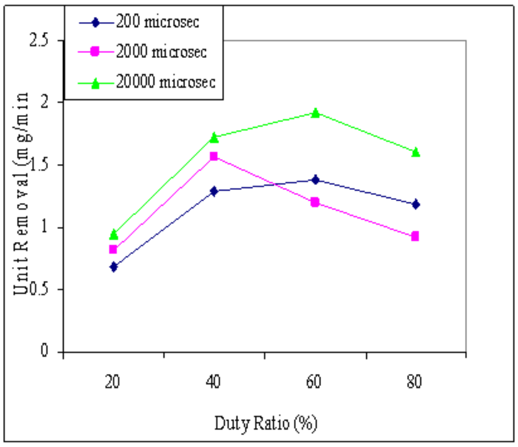


Fig. 10. *Duty ratio Vs Unit Removal at 20 g/l and 3 V for different pulse period.*

The off-time serves two functions simultaneously i.e. one due to no machining during this period, reaction products are not formed and secondly it helps two remove the dissolution products by flushing the electrolyte. Generally, on-time must be less than the off-time then only it is possible to remove reaction products completely during off-time, which were formed during the previous half-cycle (on-time), and keep the IEG ready for next half-cycle (on-time). Maintaining the machining zone in clean condition improves the dissolution rate intern increases the UR. At 20% duty ratio, the on-time is much less than the off-time. Reducing the on-time also affects the average machining current and reduces the current density subsequently linear dissolution, which results lower UR. Higher duty ratios i.e. 60% and 80% cause lesser unit removal because pulse on-time is more than pulse off-time. So the reaction products which are formed during machining could not be flushed out completely during pulse off-time that disturbs the linear dissolution.

5.2.2. Variation Side Gap with Pulse Period for Different Duty Ratio

Figure 11 depicts the micro second pulse period effect on side gap at different duty ratio as stated in the previous set of experiments. From the figure it can be observed that side gap is increasing with pulse period. Due to larger pulse period, the on-time pulse duration increases and improves the dissolution not only in linear direction but also in lateral direction that reflects more material removal from the larger surface area of the workpiece intern causes more side gap. Anodic dissolution becomes more localized by the application of shorter pulses. Stray current flow in lateral direction can be reduced by insulating the microtool properly which intern reduces the lateral dissolution. The pulse on-time increase the reaction products and these products cannot be flushed away completely during the short span off-time, which intern results accumulation of reaction products and simultaneously disturbs dissolution process. Sometimes, these reaction products may struck to the micro tool and generate micro sparks that destroys the surface integrity and accuracy intern more side gap. Pulse off-time is more; the possibility of achieving lower side gap is more. Increase of pulse off-time helps to dissipate Joule heat from the machining zone, prevents bubble formation and allows easy removal of sludge, which intern increases the linear dissolution and reduces the material removal from the larger area of the workpiece i.e. overcut. At 80% duty ratio, side gap is higher at all pulse period condition. At 80% duty ratio, pulse on-time is more than pulse off-time. During pulse on-time, dissolution takes place and these reaction products were not flushed away effectively during off-time. So, the reaction products disturb the dissolution process and affecting more material removal from the larger surface area of the workpiece that causes the increment in side gap. At 200 µsec pulse period, side gap is low for 20% duty ratio condition. Since the machining was performed at a very low parametric condition, side gap differences among various duty ratio conditions are also very small. Shorter pulse period reduces the pulse on-time and also performing experiments with 3V machining voltage and 20% duty cycle ratio, results very low current density. Since the IEG was maintained as smaller value, the current density in the IEG is higher than the one of the surrounding gap i.e. lateral side. Hence, the anodic reactions are less in lateral side that reduces the over cut intern side gap. Short pulse period with smaller duty cycle ratio are preferable for achieving good surface integrity and machining accuracy.

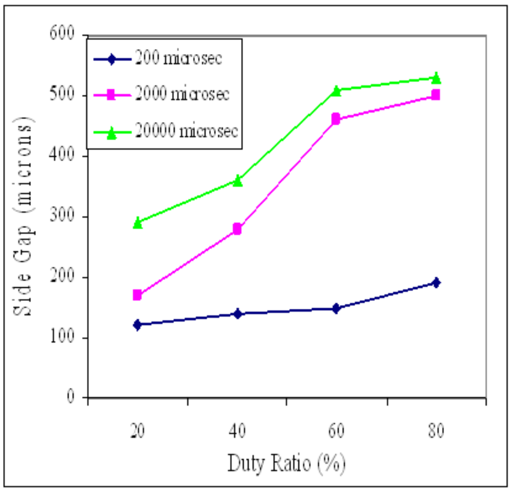


Fig.11. *Duty ratio Vs Side Gap at 20 g/l and 3 V for different pulse period.*

5.2.3. Analysis of SEM Micrographs

Figure 12 exhibits the SEM micrograph of machined micro hole at 20 g/l electrolyte concentration, 5V machining voltage, 20% duty ratio and 2000 µsec pulse period. From figure, larger side gap can be noticed on the machined micro hole but the generated micro hole is circular. Uneven surface integrity and pileup of the reaction products near the exterior periphery of the micro hole can also be observed. At lower duty ratio i.e. 20% (on-time is less than the off-time), machining reaction products can be effectively removed during off-time, which intern improves the dissolution process. Increase of dissolution rate not only in linear direction but also in lateral direction that causes larger dimension of the micro hole due to higher pulse period i.e. 2000 µsec and machining voltage i.e. 5 V, which intern reduces the accuracy. Figure 13 depicts SEM micrograph of the machined micro hole at 20 g/l electrolyte concentration, 3V machining voltage, 20% duty ratio and 200 µsec pulse period, which has been scanned by SEM without tilting the job/workpiece. To highlight circularity and machining accuracy of machined micro holes, jobs have been scanned by SEM without tilting. Good surface integrity and accuracy of the machined micro hole can be observed. Performing machining with low voltage and short pulse period, reduces the dissolution rate and reaction products, and these reaction products can be removed effectively during off-time since dissolved reaction products are less as well as the off-time pulse duration is more than on-time, which intern reduces the side gap and leads to higher accuracy and surface integrity. Fig. 14 shows the SEM micrograph of the machined micro hole periphery at (a) 20 g/l, 3V, 20% & 2000 µsec, (b) 20 g/l, 5V, 20% & 2000 µsec and (c) 20 g/l, 3V, 20% & 200 µsec. From figure it can be clearly observed that at 20 g/l, 3V, 20% & 200 µsec i.e. (c) produces better accuracy and good surface quality micro holes where as in the other two conditions i.e. (a) and (b) burrs, pits, unevenness and micro spark affected area can be observed.

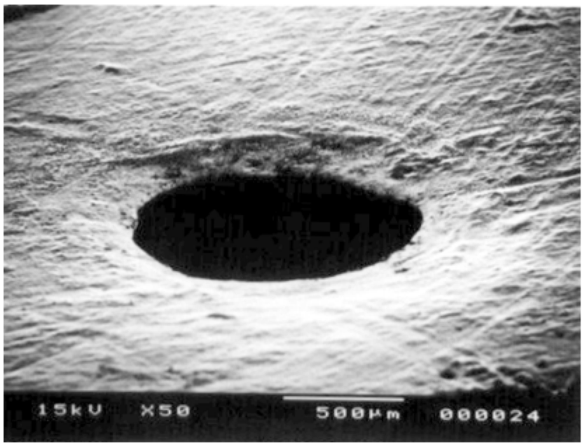


Fig.12. *SEM Micrograph of machined micro hole (20 g/l elect. conc., 5V m/c voltage, 20% duty ratio and 2000 µsec pulse period).*

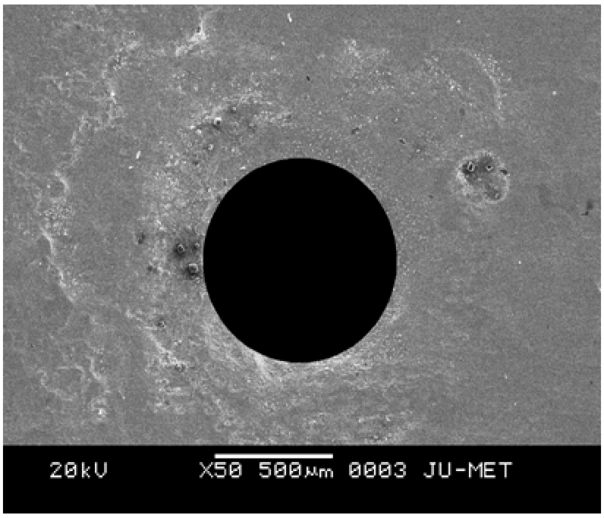


Fig.13. *SEM Micrograph of machined micro hole (20 g/l elect. conc., 3V m/c voltage, 20% duty ratio and 200 µsec pulse period).*

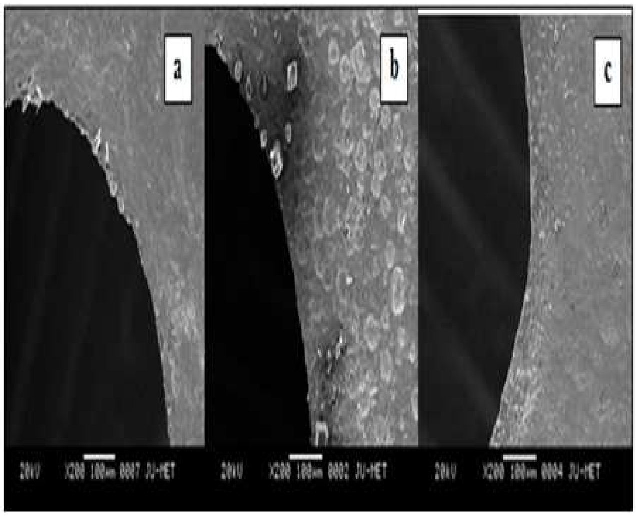


Fig.14. *SEM Micrograph of machined micro holes periphery at (a) 20 g/l, 3V, 20% & 2000 µsec, (b) 20 g/l, 5V, 20% & 2000 µsec and (c) 20 g/l, 3V, 20% & 200 µsec*

6. Conclusions

The present research mainly consists of experimental investigation on the Electrochemical Micromachining (EMM) system with short pulse period and different duty ratio's, and analysis of the acquired data to study the influence of short pulse period and duty ratio on micromachining criteria such as UR, machining accuracy and machining speed phenomena. The experimental analysis highlights that the electrochemical micromachining criteria like UR, accuracy in EMM are greatly influenced by the various predominant process parameters i.e. electrolyte concentration, machining voltage, pulse period and duty ratio considered in the present study. Based on the results and discussions, the following major conclusions can be made.

It is clear from the various graphs that the accuracy is reduced with the increment of different machining parameters where as UR is increased with the increment of different machining parameters.

Shorter pulse period machining voltage produces lower side gap and it also increases the unit removal. Lower duty ratio power supply i.e. off-time is more than on-time of the pulse period also reduces the side gap.

The detailed analysis of SEM micrographs of the machined micro holes and voltage graphs establishes the fact that selection of optimal process parametric combination is essential to achieve higher machining accuracy and better surface integrity of the micro machined products.

It has been observed from the analysis of the test results that at 200 μsec pulse period, 20% duty ratio, 3V machining voltage and 20 g/l electrolyte concentration, better accuracy can be achieved with highest possible amount of material removal and optimum machining speed.

The present experimental values and subsequent discussions and analysis on the effect of short pulse period and duty ratio in EMM will provide the guidelines to the researcher to develop the operating strategy of EMM for effective utilization of the process in the area of micromachining for precision manufacturing industries

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