Complex 3D Shape Generation on Ti6Al4V by EC Milling: A New Approach

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Abstract

Electrochemical milling (EC milling) is employed most extensively for the fabrication of complex shaped features on various HSTR alloys e.g titanium and nickel alloys so far due to its process simplicity and many superior advantages. Electrochemical milling (EC milling) avoids complex electrode design which is often a burden in sinking ECM. The process of EC milling is similar to conventional ECM where the material is removed by a simple geometric tool following a predefined path in a layer-by-layer fashion. This present research work intends to investigate the influence of process parameters on performance characteristics and viability of making various complex shape features by EC milling process on HSTR material e.g Ti6Al4V. In this work, feed rate and frequency were taken as process parameters where as overcut and surface roughness were selected as performance characteristics of EC milling. At first several simple slots were cut for the selection of suitable range of different process parameters. Comparatively more complex shaped features were machined on Ti6Al4V using three different electrolytes by varying feed rate and frequency followed by the corresponding effects on various performance characteristics were studied. It was observed that NaCl(0.5M)+$NaNO_3$(0.5M) mixed electrolyte gave better result compare to the other two electrolytes as far as accuracy and surface finish of the features were concerned. Finally, some complicated linear as well as non-linear profiles were successfully machined with those process parameters and their suitable range.

Keywords: Electrochemical milling, complex shaped feature, Titanium alloy, feed rate, frequency, different electrolytes

1. INTRODUCTION

With the development of different field starting from defence to medical industry, everywhere more complex shaped products of high strength temperature resistance (HSTR) materials like titanium and nickel alloys are being popular day by day. Titanium and its different alloy are one of the most capable materials for different applications e.g defence, biomedical, aerospace industries etc for its excellent material properties e.g corrosion resistance, high strength-to-weight ratio and biocompatibility [1]. In conventional machining processes, cutting tools have to be made of a material that is harder and stronger than that of the workpiece so, any kind of cutting tools are not really suitable to machine these types of high strength temperature resistant (HSTR) materials. The disadvantage of using harder and stronger cutting tools can be overcome by resorting to non-conventional processes such as electrical discharge machining (EDM), laser beam machining (LBM) and electrochemical machining (ECM). As EDM and LBM is the thermal process thus heat-affected zone, residual stresses and sometimes even surface cracks are also present in the workpiece. Electrochemical machining (ECM) is one of the most promising non contact type non-conventional machining processes where metal is removed in an electrolytic cell by means of anodic dissolution with no tool wear.

Electrochemical milling is a modified process of traditional electrochemical machining technique which is able to machine any kind of electrically conducting material irrespective of their mechanical properties e.g its strength, hardness, toughness etc. [2]. It has also potential to make any kind of 3D shaped feature, contour profile with a great precision by a simple shape tool [3]. The influence of process parameters like voltage, on-time and frequency of pulse generator, electrolyte flow etc on the machining performance such as material removal rate (MRR) and accuracy on micro groove machining by micro ECM have been investigated [4]. Researchers have reported two methods of blind micro channel generation i.e. the scanning machining layer by layer method and the sinking and milling method [5]. In macro filed, researchers have already been made human shape protrusion by EC milling process using sodium nitrate (10% $NaNO_3$) under DC voltage source [6]. Some slots have already been made in macro range and comparative effects of using pulse DC voltage and constant DC voltage have been studied [7]. Experiments on cylindrical and flat surfaces using ball end electrode have already been performed to verify the results with the estimated analytical data [8]. Some experiments have already been carried out by square shaped tool electrode followed by comparison of surface roughness with predicted data model and the theoretical assumptions [9]. So, from literature survey it can be figured out that EC milling will find great potential for cost effective production of any intricate 3-D shaped features on difficult-to-cut HSTR materials.

Till date very limited research works have been carried out in EC milling at macro domain. Considering all the efforts made by various researchers and also understanding the emerging trend of EC milling domain, it is needed to explore the potential use of EC milling technique to generate various complex features on different HSTR materials. It can also be found out from literature survey that the various performance characteristics of EC milling vary with the different process parameters so, it is felt that there is a urgent need of the selection of most influencing process parameters on the responses of EC milling operation for successful machining of Ti6Al4V. Therefore, in this paper attempts have been made to investigate the influence of different process parameters e.g tool feed rate and frequency on various performance characteristics e.g overcut and surface roughness followed by generation of linear as well as non-linear profiles with those process parameters and their suitable range in macro domain of EC milling.

2. ADVANTAGES OF EC MILLING

A conventional sinking-ECM consists of moving a predefined shape electrode into the workpiece and a considerable effort is

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required to design a complex 3D shape tool for die-sinking and it is usually done by various complex methods. The time and effort is required to design and fabricate the tool and that is also reflected in the cost of the workpiece. The difficulties of tool design in sinking-ECM can be avoided to a large extent if the workpiece could be electrochemically machined using a tool having a very simple geometry like rectangular, spherical or cylindrical cross section. This tool moves along a predefined path in a layer-by-layer fashion to achieve a desired geometry as in conventional milling over the workpiece surface. One of the major advantages of EC milling is relatively larger area can be machined with the help of simple shaped smaller dimensional tool. In EC milling same amount of current density can be achieved with relatively lesser amount of current than sinking ECM due to smaller electrode surface area.

3. PRINCIPLE OF EC MILLING

Principle of EC milling is same as ECM process which uses electrical current to remove the metal from the workpiece. Electrochemical reactions takes place on the job electrode, when a potential difference is applied across the cathode (tool electrode) and anode (job electrode), then the metal is dissolved from anode. Fig.1 shows the principle of EC milling by CNC-ECM with a cylindrical tool electrode. In the process, the workpiece is connected to the positive terminal and the tool is connected to the negative terminal of the DC pulse power supply. The electrolyte (a highly conductive inorganic salt solution such as, sodium chloride, sodium bromide, sodium nitrate etc.) is pumped from the tank to the working gap with the high pressure (0.5Mpa - 2MPa) and high rate (6-30 m/s) through a filter. Different complex profiles can also be generated on the work surface by controlling the relative movement between tool and the job along with X, Y and Z axis. The movement of the X, Y and Z axis are controlled by CNC control system.

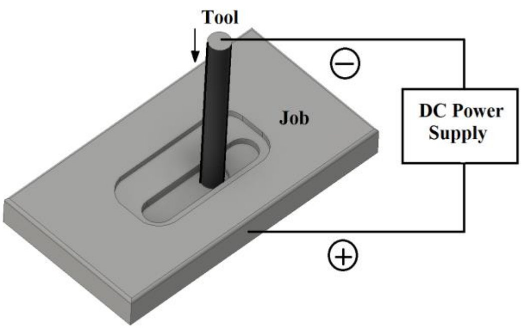

Fig.1 principle of EC milling

4. EXPERIMENTAL PLANNING

A CNC controlled X-Y-Z non-linear stage with the resolution of 0.325 micron along with a bi-polar 20V-100A pulse DC power supply has been adapted for this research work. Experiments of EC milling were carried out on titanium base super alloy (Ti6Al4V) plate to demonstrate the effects of machining parameters on the various performance characteristics. For the experiments, a cylindrical tool of SS-310 having diameter of 1.5 mm and a rectangular flat plate of 5 mm thick Titanium grade-V were chosen as the tool and the job respectively.

In ECM, choice of the electrolyte is very important. Highly concentrated NaCl electrolyte has been used for fast machining in the conventional ECM whereas, in macro ECM, types and concentration of electrolyte should also be chosen very carefully. Several preliminary experimentations have been done with various electrolytes and their different concentrations to find out the proper electrolyte and the optimal concentration for high accuracy machining of Ti6Al4V. After the preliminary experimentations, it was observed that EC milling of Ti6Al4V was suitable for using NaCl, NaBr and $NaNO_3$ electrolyte individually. But, machining performance was not so remarkable to consider using NaCl and NaBr electrolyte distinctively. So, in this experimentation two electrolytes were mixed such a way that problem encountered due to the individual electrolyte can be overcome. It was also observed after the preliminary experimentations that for a very low concentration of electrolyte, the depletion of ions prevented uniform dissolution and caused unstable machining. However, for a very high concentration of electrolyte, accuracy of the machined profile was deteriorated because of high concentration of ions. So, in this study three types of electrolytes e.g NaCl(0.5M)+NaBr(0.5M), $NaNO_3$(1M) and NaCl(0.5M)+$NaNO_3$(0.5M) were used separately considering the stability and accuracy of the machining.

Initially, several simple slots were machined on the job to find out the suitable range of selected process parameters. For this study, three types of electrolyte were used separately and effects of these electrolytes on important performance characteristics of EC milling with changing feed rate and frequency were studied.

Experiments were conducted at different feed rate and frequency to machine a slot on the job. In the preliminary experiments it was seen that above feed rate of 0.05 mm/sec short circuit phenomenon was found whereas, more over cut was found for feed rate below 0.02 mm/sec. So, feed rates were varied from 0.02 mm/sec to 0.05 mm/sec with the increment of 0.01mm/sec. In the preliminary experiments, it was also found out that performance characteristics were varied significantly for 5 kHz to 13 kHz, but at 13kHz frequency, accuracy and surface quality of machined profile was not so good. So, Frequency was varied from 5 kHz to 12.5 kHz with the increment of 2.5 kHz with three different types of electrolyte as shown in Table 1 and consequent effects were noted. Short circuit was occurred using $NaNO_3$ (1M) electrolyte on further increment of feed rate of 0.04mm/sec at 12.5 kHz frequency. For this reason during entire experimentation frequency were fixed at 10 kHz while tool feed rate was varied and similarly, tool feed rate was kept constant at 0.04mm/sec while frequency was varied. Other process parameters were kept constant at the time of machining as depicted in Table 2.

Table 1 Table for process parameters

Machining Condition	
Feed rate (mm/sec)	0.02, 0.03, 0.04, 0.05
Frequency (kHz)	5, 7.5, 10, 12.5
Types of electrolyte	$NaNO_3$(1M), NaCl(0.5M)+NaBr(0.5M), NaCl(0.5M)+$NaNO_3$(0.5M)

Table 2 Table for fixed process parameters

Machining Condition	
Duty ratio	0.4
Initial Inter Electrode gap (mm)	0.5
Feed rate along 'Z' axis (mm/sec)	0.02
Milling layer thickness (mm)	0.2
Input current (A)	12
Type of current	square pulse
Input DC voltage (V)	20

5. RESULTS AND DISCUSSIONS

Experiments were conducted to find out the optimal process parameters which could result low overcut, smaller surface roughness and most accurate profile. In the subsequent set of research, EC milling of Ti6Al4V using three different electrolytes by varying feed rate and frequency followed by the corresponding effects on various performance characteristics were studied.

a. Effects of feed rate and frequency on overcut

In ECM, overcut is occurred due to the stray current effect for the bare portion of the tool tip. From the Fig.2 it can be seen that overcut was continuously decreased with increasing feed rate keeping frequency constant at 10kHz. This is because with increasing feed rate a unit area of the workpiece reacts with the tool for a shorter time so, material removal rate decreases which leads to decrement of overcut. Using NaCl+NaBr electrolyte, width overcut was drastically decreased with increasing feed rate. In case of using NaCl+$NaNO_3$ and $NaNO_3$ electrolyte trend of the graphs are almost same, overcut was decreased gradually with increasing feed rare upto 0.04mm/sec, followed by almost same value. Highest value of overcut was found using NaCl+NaBr but, decreasing rate of overcut was more compared to other two types of electrolyte. In case of using $NaNO_3$ electrolyte least value of overcut was observed. More material removal as well as more overcut is occurred using NaCl+NaBr electrolyte than using NaCl+$NaNO_3$ electrolyte [10]. Because of more passivating nature of $NaNO_3$ than the other two types of electrolyte, it is observed that the values of overcut are much less for $NaNO_3$ electrolyte.

From the Fig.3 it is also cleared that overcut was varied significantly for varying frequency when feed rate was fixed at 0.04 mm/sec. Using NaCl+$NaNO_3$ and $NaNO_3$ electrolyte, trend of the graphs are almost same, overcut was decreased upto 7.5 kHz frequency then remained same after that decreased at subsequent frequency. For using NaCl+NaBr electrolyte, overcut was decreased steadily with very low rate. As frequency is inversely proportional to the machining on-time so, MRR as well as overcut is decreased when frequency is getting increased. Upto 10kHz frequency overcut was found more using NaCl+$NaNO_3$ electrolyte whereas, lowest overcut was found using $NaNO_3$ electrolyte because of the order of passivating nature of all of the three electrolytes. The range of highest overcut and lowest overcut for a particular electrolyte was found low for varying frequency compare to varying feed rate. The reason behind the nature of those graphs for varying feed rate and frequency has been discussed already in the earlier section.

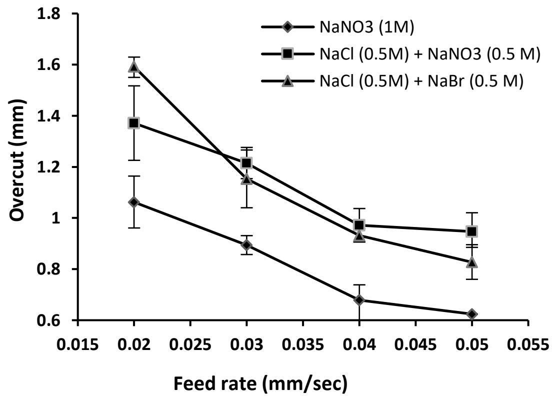

Fig.2 Effect of feed rate on overcut

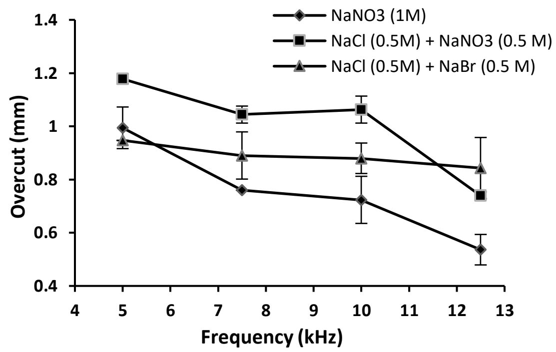

Fig.3 Effect of frequency on overcut

b. Effects of feed rate and frequency on surface roughness

On the contrary with previous response, from the Fig.3 it is clearly observed that surface roughness was increased with the increment of feed rate. Using $NaNO_3$, surface roughness was more compare to rest of two types of electrolyte. Using NaCl+NaBr electrolyte, surface roughness was moderate and using NaCl+$NaNO_3$ electrolyte, surface roughness was found excellent comparing with other two types of electrolyte. With the increment of feed rate a unit area of the workpiece reacts with the tool for a shorter duration and after a certain value of feed rate, electrochemical dissolution may not occurs homogeneously at the surface of the workpiece. So, surface quality is deteriorated with the increment of feed rate.

Sodium nitrate based electrolytes showed the formation of a relatively thick and insoluble TiO_2 scale on the surface of the machined profile. So, poor surface quality was obtained using $NaNO_3$ electrolyte. NaCl+NaBr electrolyte is responsible for the formation of rutile and sticky $TiCl_4$ and $TiBr_4$ species which are precipitated on machined surface. Those precipitated particles are not easily flushed away thus, deteriorates surface quality. Sludge produced during machining using NaCl+$NaNO_3$ electrolyte is insoluble, non-sticky and lighter. So, this sludge is easily flushed away from the machine zone, hence excellent surface finish was obtained using NaCl+$NaNO_3$ electrolyte.

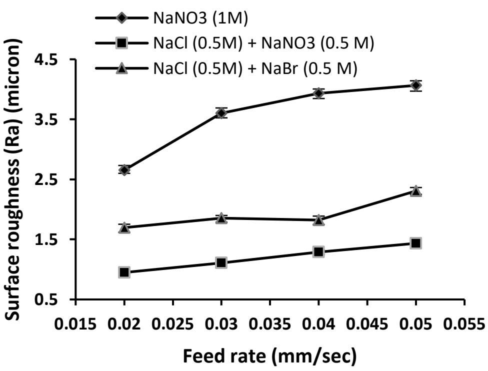

Fig.4 Effect of feed rate on surface roughness

From Fig.5, it can be clearly reported that surface roughness was increased significantly with the increment of frequency. It is well known that frequency is the inverse of the time period of single cycle. The time period of single cycle for 10 kHz frequency and 5 kHz frequency are 100 micro second and 200 micro second and at 10 kHz frequency and 40% duty ratio, machining on time for a single cycle is 40 micro-second and for 5 kHz frequency and 40% duty ratio machining on time for a single cycle is 80 micro second. So, it can be clearly understood that for a single cycle the machining on time is increased for decreasing frequency when duty is fixed. Again, the effective machining time is reduced with the increment of frequency due to the double layer charging time phenomena. Effective machining on time for a single cycle is increased for reducing frequency. Hence, homogeneous electrochemical dissolution is deteriorated with the increment of frequency. In this case also, using $NaNO_3$ electrolyte surface finish was found worst comparing with other two types of electrolyte whereas, using $NaCl+NaNO_3$ electrolyte, best surface finish was achieved.

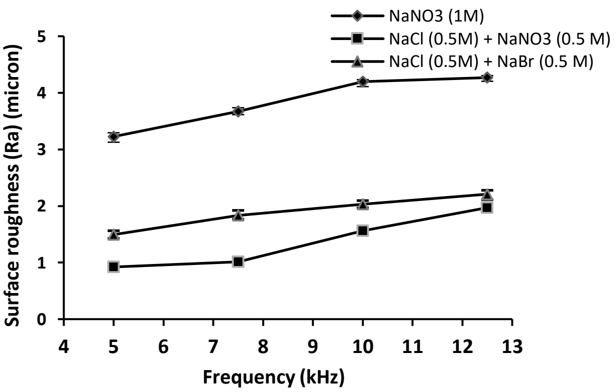

Fig.5 Effect of frequency on surface roughness

In this experimentation, best surface finish has been achieved at at 0.02mm/sec of feed rate and 5kHz frequency using NaCl (0.5M)+$NaNO_3$(0.5M) electrolyte. It is also been observed that best machining has been observed at 0.04mm/sec and 10kHz frequency as far as accuracy of the machining profile is concerned.

In the next set of research some linear as well as non-linear profile has been generated on Ti6Al4V using NaCl (0.5M) + $NaNO_3$(0.5M) electrolyte at 0.04mm/sec and 10kHz frequency.

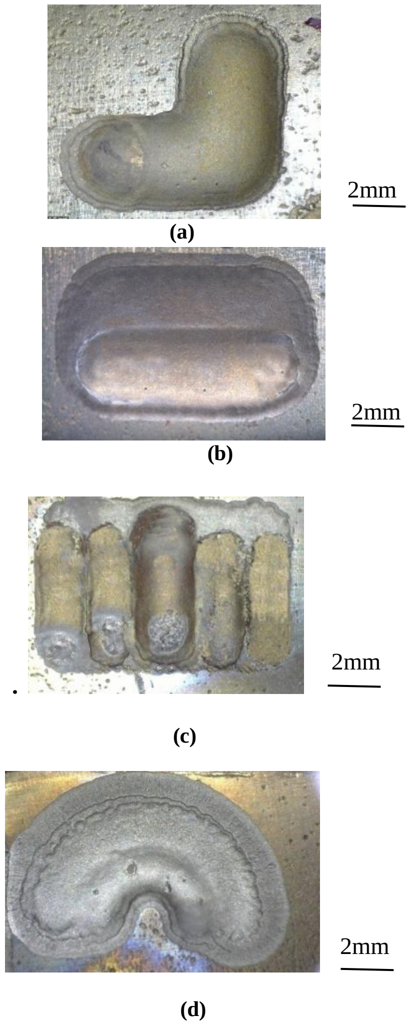

Fig.6 Photographic view of the machined profile using NaCl(0.5M)+NaNO3(0.5M) electrolyte at feed rate of 0.04mm/sec and 10 kHz frequency. (a) 'L' shaped profile (b) Two stepped profile (c) Three stepped profile (d) Non linear two stepped profile

Photographic view of the linear as well as non linear machined profile using NaCl(0.5M)+NaNO3(0.5M) electrolyte at feed rate of 0.04mm/sec and 10 kHz frequency shown in Fig. 6. In the Fig. 6(a) 'L' shaped feature has been machined to study the corner effect of the machined profile. Two step as well as three step features has been generated not only to study the effect of passes on the depth but also to study the effect of passes on accuracy of the step and which has been depicted in Fig. 6(b) and Fig. 6(c) respectively. Fig. 6(d) depicted a non linear stepped profile.

6. CONCLUSIONS

In this study, at 0.05 mm/sec of feed rate and 12.5 kHz of frequency with $NaNO_3$(1M) electrolyte, least overcut is observed whereas, best surface finish is achieved at NaCl(0.5M)+$NaNO_3$(0.5M) electrolyte at 0.02mm/sec of feed rate and 5 kHz of frequency. The investigations have also shown that EC milling of complex shaped features on Ti6Al4V are feasible to create with a very simple geometrical tool. Outcomes of this experimentation could be explored the effective utility of EC milling of Ti6Al4V at macro domain.

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References

[1] Wang D, Zhu Z, He B, Ge Y, Zhu D. "Effect of the breakdown time of a passive film on the electrochemical machining of rotating cylindrical electrode in $NaNO_3$ solution", Journal of Materials Processing Technology, vol. 239, 2017, pp 251–257.

[2] Rajurkar K P, Zhu D, Mcgeough J A, Kozak J, DeSilva A. "New developments in electro-chemical machining" CIRP, vol. 48, 1999, pp 567–579.

[3] Kim B H, Ryu S H, Choi D K, Chu C N. "Micro electrochemical milling", Journal of Micromechanics and Micro engineering, vol. 15, 2005, pp 124–129.

[4] Chen C, Li J, Zhan S, Yu Z, Xu W. "Study of micro groove machining by micro ECM", Procedia CIRP, vol. 42, 2016 , pp 418 – 422.

[5] Ghoshal B, Bhattacharyya B. "Investigation on profile of micro channel generated by electrochemical micromachining", Journal of Materials Processing Technology, vol. 222, 2015, pp 410–421.

[6] Hindujaa S, Pattavanitch J. "Experimental and numerical investigations in electro-chemical milling", CIRP Journal of Manufacturing Science and Technology, vol. 12, 2016, pp 79–89.

[7] Vanderauweraa W, Vanloffelta M, Perezb R, Lauwersa B. "Investigation on the performance of macro electrochemical milling", Procedia CIRP, vol. 6, 2013, pp 356 – 361.

[8] Kozak J, Chuchro M, Ruszaj A, Karbowski K. "The computer aided simulation of electrochemical process with universal spherical electrodes when machining sculptured surfaces", Journal of Material Processing Technology, vol. 107, 2000, pp 283–287.

[9] Ruszaj A, Skrabalak Z M. "The mathematical modelling of electrochemical machining with flat ended universal electrodes", Journal of Material Processing Technology, vol. 109, 2001, pp 333–338.

[10] K. Mishra, D. Dey, B. R. Sarkar and B. Bhattacharyya, "Experimental Investigation into Electrochemical Milling of Ti6Al4V", Journal of Manufacturing Processes, 2017, vol. 29, pp 113–123.