Optimization of Electro-Chemical Micro Machining Process using Additive Manufactured Tool on Titanium Alloy (Ti-3Al-2.5V) by Taguchi-Grey Method

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Abstract

As Electro-Chemical Micro Machining (ECMM) is one of the advanced method of machining which gives higher quality product, better efficiency and accurate machining over conventional methods, it is popular in various industries to manufacture products. Titanium Alloy (Ti-3Al-2.5V) can also be machined using ECMM process and as it has a properties of high mechanical strength, high resistance to stress corrosion cracking and excellent fatigue properties, it can have various applications in mechanical and biomedical field. Different industry working with water which is saline, needs heat exchanger for the process. Titanium Grade 9 due to its high corrosion resistance under saline conditions is preferred by these industries. This study is about optimization of input process parameters like applied voltage, electrolyte concentration, micro tool feed rate and duty ratio to get high Material Removal Rate (MRR), better Overcut on machining Titanium Alloy using Additive manufactured tool. From the investigational results, it has been observed that the additive tool for the ECMM process has significantly enhance the surface accuracy of the ECMM product with 17 volts, combination of sodium nitrate and sodium citrate (1+0.02 mol/lit), 50 % duty cycle to attained higher material removal rate.

Keywords: Titanium Alloy (Ti-3al-2.5v), Additive Tool, Hybrid Electrolyte, Optimization, Material Removal Rate, Overcut, Taguchi-Grey Method, Microscopic Analysis.

1. INTRODUCTION

Conventional Manufacturing techniques has limits for producing complex shapes, producing micro holes and micro slots,[1] tool wear, and providing limits for accuracy and precision.[2] These problems can be overcome by using Non-conventional Manufacturing techniques like Electro-Discharge Machining (EDM), Laser Beam Machining (LBM), Electron Beam Machining (EBM) and electro-chemical machining (ECM).[2] Various of the non-conventional manufacturing techniques has heat effected zone on work piece but ECM doesn't has it. So, ECM shows great step for improvement in manufacturing techniques.

Electro-Chemical Machining (ECM), which is electrochemical type of Unconventional machining process, in which controlled removal of metal by anodic dissolution where the tool is as cathode and workpiece is as anode. The electrolyte is pumped through the gap between tool and workpiece called as inter electrode gap and also completes the circuit. The shape of tool is generally the inverse copy of the shape to be machined on the workpiece. [3] Electrochemical machining is developed based on Faraday's laws of electrolysis and Ohm's law. [4] According to Faraday's law of electrolysis, when two electrodes are put in an electrolytic solution and a DC power supply is applied across those electrodes, the metal is deposited from the anode to cathode. ECM process is the reverse of electrochemical plating technique. In ECM process, anodic dissolution occurs at atomic level of the workpiece by a shaped tool due to flow of high current at relatively low potential difference between tool and workpiece through an electrolyte. As Electro Chemical Machining technique provides high surface finished, highly accurate and stress free products, it is used widely to manufacture turbine blades, high compression engines, artillery projectiles and parts for electronics and medical industries [5].

Electrochemical Micro Machining (ECMM or EMM) is ECM process done in micron level. It is done for very small size products with better control during ECM process. It is used to give micro-holes and micro-slots on stock of material with very high precision and quality. Additive Manufacturing (AM) is the process of joining materials to make product from 3D model data, usually layer upon layer. Additive Manufacturing has the special ability to form final shaped product by adding materials rather than by removing material from a large stock or sheet metal. It enables manufacturing of complex geometry with lesser processing step and minimum wastage, thus reduces time and cost for manufacturing product. It is now applied in aerospace, medical implant and electronics field.

Researches are done on ECM process based on its process parameters, Electrolyte, Tool shape and materials, and workpiece. Researches on coated tool and cryogenic tool are also done for tool electrode. This study is about machining of Titanium grade 9 as workpiece of EMM process and influence of additively manufactured tool over the process, which are yet to be studied.

2. EXPERIMENTAL SETUP

The EMM setup as in fig.1, mainly having of components, like mechanical machining unit, tool electrode feeding system (lead screw mechanism), electrolyte bath, and pulsed power supply system. The electrolyte bath is connected to a pump and a filter. The mechanical machining unit consists of work holding device, micro-tool feeding system and machining chamber. The micro-tool feed movement is achieved through the lead screw mechanism. The lead screw of the tool movement is rotated with the help of stepper motor. A pulsed power supply of 0-30V and 0-2A with the capability of controlling voltage, current, and duty cycle was used. The experimental factors were selected based on the influence of process parameters affecting the machining rate and shape accuracy of material. Taguchi method, which is a good tool to

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design and analyze the experiments conducted, is chosen for the study. It uses orthogonal array as a special design to study the parameters of experiment with a few number of experiments. This results in reduction in the cost and production time.

The MRR of material is calculated by formula and with help of weighing machine. The shape accuracy and effect on tool can be seen by optical microscope. And also the dimensions of tool electrode is measured before and after machining using profile projector. The optimal process parameters are determined by analyzing the characteristic data acquired by experiment using Minitab package software.

Fig. 1.Experimental Setup

3. EXPERIMENTS AND METHODS

This research work has been made to know the influence of additively manufactured tool on the machining characteristics of EMM for Titanium Grade 9. MRR and surface accuracy have been taken as the performance measures. L4 orthogonal array of Taguchi Method was selected based on number of controllable process parameters. Applied voltage, electrolyte concentration and duty cycle have been chosen as process parameters with Stainless Steel 316L tool electrode material in shape of sharp pencil of size 30mm long and 2mm thick but 0.4mm thick from tip. Titanium grade 9 has been decided as the work piece material of size of 40mm x 20mm x 1.7mm, the composition of the work piece is presented in Table 1. The electrolyte used for experimentation was 1mol/L of Sodium Nitrate and 1mol/L of Sodium Nitrate with 0.02mol/L of Sodium Citrate. [6] Voltage is 15V and 17V for experiments. Duty cycle has been selected as 50 and 66%. Frequency for experiment was 50 Hz. The Micro-tool feed rate of 0.4µm/min have been chosen for this experiments. Therefore, the process parameters and their levels are selected based upon the trial and error methods.

Table 1: Chemical Composition of Titanium Grade 9

Elements	Composition (%)
Iron (Fe)	0.23
Aluminum (Al)	3.01
Vanadium (V)	2.19
Titanium (Ti)	94.65

During machining the parameters are set to require based on trial of orthogonal array. The machining is done for blind hole and is done for specific amount of time. The time is fixed because machine used in process is without computer aid thus the depth of cut cannot be control but the time can be.

The MRR have been calculated by finding weight variation of material before and after machining of work piece, per machining time. And is compared for both tool in excel. The optical microscope is used to find shape accuracy of the micro-hole and effect on tool. To measure the dimension of tools profile projector was used.

Table 2: Process Parameters for the Process

Parameters	Level 1	Level 2
Applied Voltage (V)	15	17
Electrolyte Concentration (Mole/Lit)	1 - $NaNO_3$	1 - $NaNO_3$
	0 - Sodium Citrate	0.02-Sodium Citrate
Duty Cycle (%)	50	66

3.1 Steps involved in additive manufacturing process

3.1.1 Software

i. Create a CAD file of the tool (here .igs file).
ii. This file is opened in EOSRP and EOSTATE software.
iii. These software converts CAD file into .stl file which is provided by a base as a supporting structure for the model with thickness of layer during manufacturing.
iv. Then .stl file is then sent to machine.

3.1.2 Process preparation

i. The material (Stainless Steel 316L) is filled in the machine and platform.
ii. Then the work volume is filled with Nitrogen or Argon gas (Nitrogen is used here).
iii. Set the laser power (preferred 200W).

3.1.3 Process

i. After the software and preparation part the machine start.
ii. Laser is focused on metal powder which fuses into the model with the base.
iii. Once the manufacturing is done the base is removed using wire cutting method.
iv. Then the workpiece undergoes finishing processes like grinding.

4 RESULTS AND DISCUSSION

The effects of Additive tool on ECMM Titanium grade 9 workpiece, with process parameters like voltage, concentration and duty cycle, tool of stainless steel 316L both bare and Sodium Nitrate electrolyte with Sodium Citrate as complexing agent for electrolyte is investigate for MRR, shape accuracy and effect on tool and the results are listed below.

4.1 Effect on MRR

The MRR has been obtained from the weight difference of electrode before and after machining of work piece per machining time.

$$MRR = (W_{before} - W_{after}) / T \quad (1)$$

W_{before} = Weight of the piece before machining (g)

W_{after} = Weight of the piece after machining(g)

T = Machining time (hours)

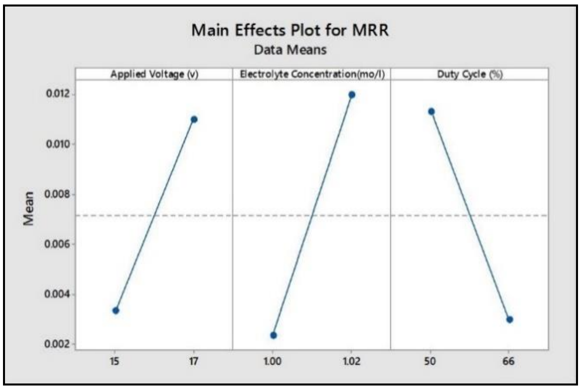

Fig. 2. Contribution of process parameter on MRR for bare tool

Figure 2 shows the contribution of process parameters on MRR. Since the deviation from the mean level line indicates momentous contribution on EMM variables, it is clear that Electrolyte with Complexing agent has the more dominant effect than the other process parameter such as applied voltage, Duty cycle. Voltage and concentration has direct relation with MRR but its inverse for relation between Duty cycle and MRR.

Fig 3. Shows that applied voltage for additive tool has more dominating effect on MRR. Here, MRR is directly proportional to Voltage and duty cycle but inversely proportional to concentration.

Thus one can clearly say for more optimum result the voltage should be kept as high as possible.

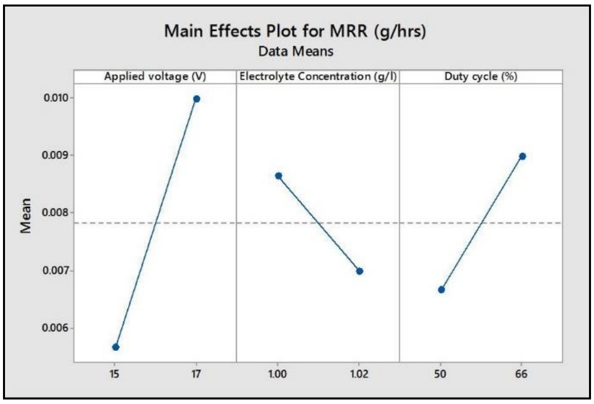

Fig 3. Contribution of process parameters on MRR for additive tool

Table 3: Comparison Between MRR For Bare Tool And Additive Tool

S. no	Voltage (V)	Concentration (Mol/L)		Duty ratio (%)	MRR (g/hrs)	
		Sodium Nitrate	Sodium Citrate		Bare tool	Additive tool
1	15	1	0	50	0.00133	0.00533
2	15	1	0.02	66	0.004	0.006
3	17	1	0	66	0.002	0.012
4	17	1	0.02	50	0.006	0.008

By Table 3 and Fig 4 it is clear that additively manufactured tool provide better MRR than bare tool. It is because the composition throughout the tool has more uniformity in additively manufactured tool as compared to conventionally manufactured bare tool.

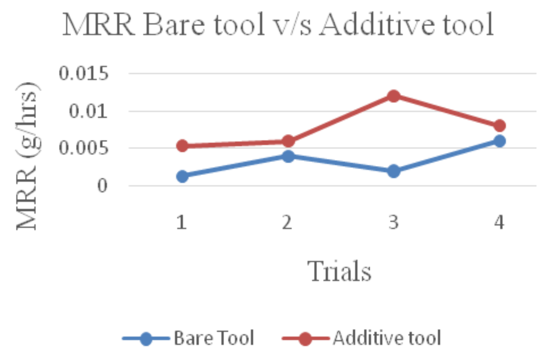

Fig 4. Comparison between MRR for bare tool and additive tool

4.2 Effect on Overcut

The quality of the micro–hole produced by ECM process on Titanium workpiece by both type of Stainless Steel tool can be measured by capturing Overcut of workpiece under Optical Microscope.

Overcut is the difference between cross-sections of the tool from the cross-section of the micro-hole produced by that tool. It is measured by subtracting radius of both tool and hole. The tool giving lower value for overcut is superior.

$$\text{Overcut} = (D_H - D_T)/2 \ldots \mu m \qquad (2)$$

D_H = Mean Diameter of Micro-hole (µm)

D_T = Diameter of Tool electrode Tip (µm)

Table 4: Comparison between overcut for bare tool And additive tool

Trials	Overcut by Bare Tool (µm)	Overcut by Additive Tool (µm)
1	25.5525	17.6575
2	21.29	16.4875
3	5.4175	4.7375
4	18.2725	9.99

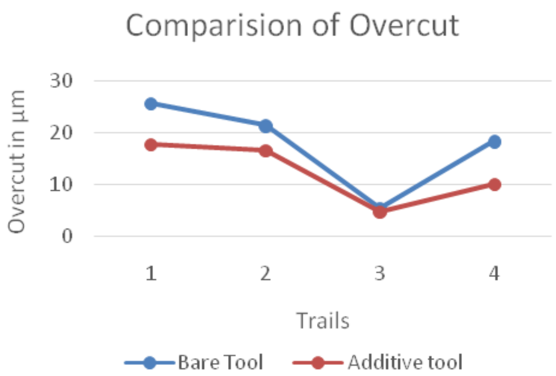

Fig 5. Comparison of tool electrode on overcut

Figure 5 shows that overcut of additive tool is better than that of bare tool. The circularity are better in additive tool because of additive manufacturing dimensional accuracy is far better than conventional manufacturing. It is because additive manufacturing create tool providing high localization effect and minimize stray current.

4.3 Optimization of Grey Relational Analysis

Conventional Taguchi method deals with single response optimization only. It may give different set of optimal combinations for multi responses. Therefore, it is needed to introduce multi response optimization technique in the process. For multi response optimization, grey relational analysis coupled with Taguchi method is employed. In this approach, the multi response can be converted into single normalized response. The grey relational optimization procedure is as follows,

1. Convert the responses into signal to noise ratio using higher the better or lower the better criterion.
2. Normalize the signal to noise ratio.
3. Compute grey relational coefficient for normalized signal to noise ratio.
4. Compute grey relational grade.
5. Rank the grey relational grade.

Table 5: Values of S/N Ratio to normalized S/N Ratio

Ex. No	Material Removal Rate	Surface roughness (μm)
	Normalized S/N ratio	Normalized S/N ratio
1.	0	0
2.	0.10044	0.09055
3.	1	1
4.	0.40029	0.59345

Table 6: Values of grey relational grade and rank

Ex. No	Grey-Relational co-efficient		Grey-Relational grade	Rank
	MRR	SR		
1.	0.3333	0.3333	0.3333	4
2.	0.3572	0.3547	0.3560	3
3.	1	1	1	1
4.	0.4546	0.5515	0.5031	2

From the table 5 and 6, it can be inferred that the values of response parameters for 3th experiment are optimized value since it is ranked 1. The optimized values are obtained from the experiment in which the grey relational grade is ranked 1 out of 4 experiments. The optimized values for various machining parameters are,

- Material removal rate is 0.012 (g/hr)
- Radial overcut is 4.7375 (μm).

These values are obtained for input parameters like applied voltage at 17 (V), electrolyte Concentration of 1 (mol/l) and duty cycle of 66 **(**%).

5 CONCLUSIONS

The machining performance of electro-chemical micro machining process parameters on machining Titanium Grade 9 with bare and additive Stainless Steel 316L tool electrodes have been evaluated. From the results of the study, the following conclusions have been drawn:

- Optimizing the Voltage for the process is best option to optimize the ECMM process.
- The MRR of additive manufactured tool is more than bare tool because the composition of additive tool has more uniformity than that of bare tool and due to strong atomic bond of metals in additive tool the conductivity of tool is increased.
- The overcut is better in additive tool because additive manufacturing dimensional accuracy is far better than conventional manufacturing, as additive manufacturing do controlled machining due to increased localization effect and less stray current

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