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Modeling and Simulation of Wire Electrochemical Turning (Wire-EC-Trg) Process

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Abstract

Micro tools are essential for the fabrication of miniaturized components and devices. Such devices find application in biomedical and healthcare industry, electronics industry, etc. Micro-fabrication by electrochemical dissolution is appearing to be the most promising technology in the modern age as it has various advantages over other similar processes, absence of recast layer, heat affected zone and thermal stresses in the machined object are some of them. During fabrication of micro tools by ECM process, it is essential to control the process and monitor the dimensions online. This may sometimes become cumbersome and eventually lead to reduction in the productivity. Hence there is a resilient need for an analytical model which can predict the final dimension of the workpiece for a given set of working parameters. The present work is focused upon generation of axially symmetric micro tools using wire electrochemical turning process. The complete process is simulated on Comsol Multiphysics software in order to study the distribution of current density in the flowing electrolyte and on the surface of workpiece and tool. With the help of simulation results and after making certain assumptions, a mathematical model which uses the variation in minimum inter electrode gap (IEG) to predict the final diameter of micro tool is developed. This model is verified experimentally and decent results within the error range of 2-4 % are obtained. In the final part of this work two micro tools are fabricated, one on copper having diameter of 200 µm and l/d ratio of 75 and other on stainless steel with diameter of 40.27 µm and l/d ratio of 6.5

Keywords: Mean inter electrode gap, Current density distribution, Resistance model, Regression curve.

1. INTRODUCTION

ECM process is widely used in industries like aerospace, automobile and defence. This process is also suitable for cutting intricate shapes on difficult to machine material. However due to the problems like tool design, electrolyte's corrosive behaviour and dimensional accuracy, ECM is yet to be explored to its full potential. With the growing demand of miniaturized product, the need of precise micro tools is increasing day by day. Fabrication of these micro tools is quite difficult using conventional machining methods. Among other competitive processes like EDM, LBM, etc., ECM has its own advantages over the other advanced machining processes in fabrication of micro tools. Absence of HAZ and recast layer makes ECM more compatible to manufacture defect free miniaturized components. Since material is removed ion by ion, so hardness of workpiece doesn't put any kind of restriction on machining. Electrochemical turning, a recent advancement of ECM process has the potential to manufacture large axially symmetric workpieces. Micro tools, which are otherwise difficult to produce using conventional turning and milling due to the generation of excessive stress at these sections which otherwise distort the geometry of the final component can also be fabricated by electrochemical turning. Significant work is not yet being reported which deals with the modelling of wire electrochemical turning process in order to generate features of sub-micron dimensions.

1.1 Literature Review

Jain and Pandey (1980) evaluate frontal gap along the axis of the workpiece by the use of modified ECM theory, which takes into account effects of simultaneous variations in temperature, electrolyte conductivity, current density and other related parameters [1]. Bejar &Eterovich (1995) examined wire ECM for the cutting of mild steel with passivating electrolyte of $NaNO_3$ [2]. Wire ECM has been studied by various researchers across the globe for optimizing its different process parameters. Maeda et al. (1984) studied the effect of processing parameters, such as electrolyte flow rate, nozzle diameter, and current density on the maximum feed rate of cutting during WECM [5]. Good dimensional control of an electrochemically-machined component is normally difficult to obtain, the design of the tool generally being a serious problem. Jain and Rajurkar (1991) design the tool for ECM by integrated approach method [6].Hofstede and Brekel investigated different geometry of electrodes like, box shaped electrode and plate electrode in electrochemical turning process [7]. Dietz et al. (1979) investigated the electrochemical turning process for electrodes inclined at an angle. They derived links between the minimum inter-electrode gap, geometry of electrode and feed rate [8]. Ghabrial et al. (1992) investigated the electrochemical grooving operation while using a shaped tube electrode. With increase in tool feed rate groove width of cut also increase [9]. Taweel et al. (2010) investigated wire electrochemical turning operation.

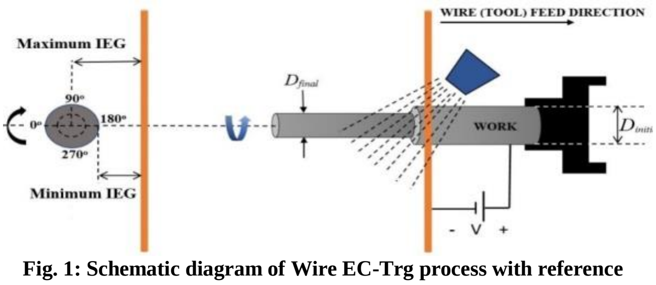

Fig. 1: Schematic diagram of Wire EC-Trg process with reference angle on workpiece

They studied the effect of various input parameters on MRR and surface finish of the turned workpiece. They reported that MRR increases with increase in RPM [10]. Taweel et al. (2010) in their work studied wire electrochemical grooving operation and concluded that groove width largely depends on wire diameter and feed. [11]. Mathew and Sundaram (2012) fabricated micro tool of 13.4 µm diameter. They predicted this diameter by a mathematical model and the error was around 6-8

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% [12]. Chen et al. (2016) study micro groove operation using jet electrolyte in ECM. It was observed by them that the taper of groove side walls and the corner radius increase with increase of pulse voltage and on-time [13].

Zhaoyang et al (2011) demonstrated a simple method of fabrication of micro tool by electrochemical dissolution known as drop off method; in which anodic dissolution occur at the air electrolyte interface. However, due to the formation of thin diffusion layer at the interface of electrolyte and workpiece. The particles in the diffusion layer are acted upon by gravity and reduce the dissolution rate near the end of the tool. Fig.2 shows the schematic of this process. As the potential is increased further necking occurs and micro tool drops off leading to the generation of tapered micro tool. Fig.3 shows a typical micro tool fabricated using drop off method. Despite the simplicity of this process, fabrication of micro tools with uniform diameter throughout the length is very difficult. [14]

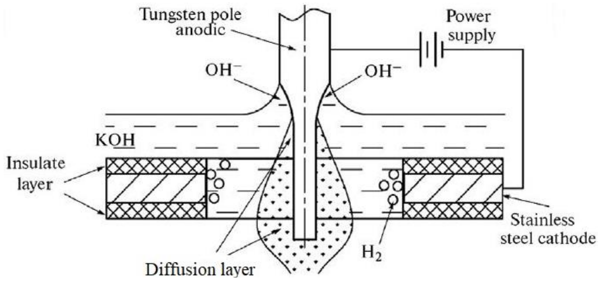

Fig. 2: Schematic diagram of drop-off method [15]

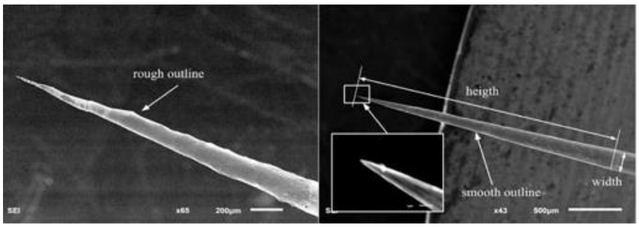

Fig.3: Micro tool fabricated by drop-off method [15]

In the present work, the capability of wire EC turning process to fabricate micro tools of uniform diameter throughout its length is studied. As the workpiece is kept horizontal, each point on the workpiece is at the same height from the datum axis. Hence, the effect of gravity on the location of diffusion layer on workpiece surface is eliminated. The complete process is simulated on Comsol Multiphysics software in order to study the distribution of current density around the circumference of the workpiece. The simulation results show that current density distribution around the workpiece is dependent on IEG and diameter of the workpiece. Taking this into account a relationship between IEG and workpiece diameter is derived such that the current density at angle 90^0 and 270^0 (Fig.7) is less than one percent of the maximum current density (which is at 180^0). With the help of simulation results and after making reasonable assumptions, a mathematical model is developed to predict the final diameter of tool using mean inter electrode gap between wire and workpiece. An experimental set-up is fabricated on which this model is verified experimentally. The experimental results show that results predicted in the model are in good agreement with the theoretical prediction. Error between theoretical prediction and experimental output was around 2-5 %.

2. EXPERIMENATL SET-UP

The workpiece holder & electrolyte basin are mounted on X-Y drive, interfaced with computer using Arduino microcontroller. Regulated D.C. power supply with voltage rating from 0 to 32 volts & minimum resolution for the current as 0.01 A is used. Electrolyte is delivered from the flexible delivery tube through a pressurized electrolyte tank. Wire is held tight in C-clamp. Workpiece is rotated with the help of a servo motor of rating 12 V and 0.6 A. Shaft made of brass is attached to the motor shaft with the help of a flexible coupling and is supported by two bearings to restrict its lateral movement. This is to ensure proper centring of the shaft. At the end of this shaft workpiece is mounted with the help of collet of specification ER 11 with taper angle of 8^0. The schematic diagram of the set-up is shown in the Fig.4.

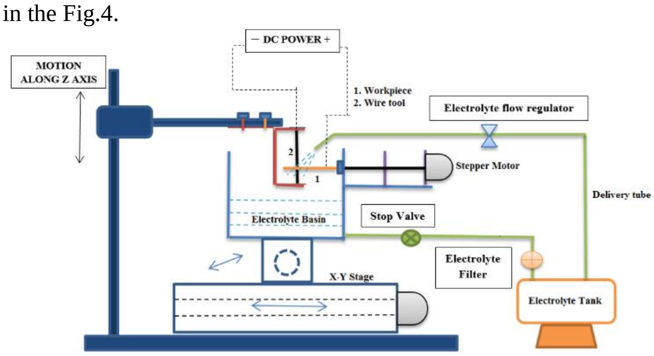

Fig. 4: Schematic diagram of Wire EC-Trg set-up

3. MODELING OF WIRE EC-Trg PROCESS

In this section, a mathematical model is developed in order to predict the final diameter of workpiece after machining. The assumptions made for this model and their justifications are discussed in section 3.1.

3.1 Assumptions

Assumption 1: At any instant, material is removed from the projected half circumference of workpiece.

This assumption can be understood from the simple circuit model of tool and workpiece.

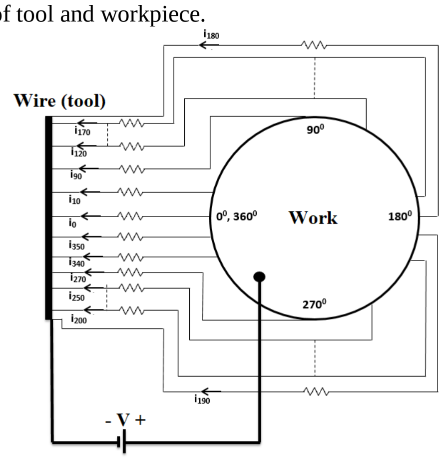

Fig.5: Schematic diagram of equivalent circuit model

As the whole of the workpiece surface is enclosed by the envelope of electrolyte, the material will be removed at a non-uniform rate from the whole circumference. However, for the material to be removed from only frontal half of the workpiece (270^0-0^0-90^0) the current flowing must be in the order, $i_0 > i_1 ...... > i_{90} > i_{91} \approx i_{92} ...... \approx i_{180} ... \approx i_{270} \approx 0 < i_{271} < i_{272} .... < i_{359} < i_{360} = i_0$ ..... ***(i)***

The resistance along different path for current flow can be adjusted so as to achieve this order; this can be done by varying the minimum IEG and the workpiece diameter in such a way that the current density at the opposite face of the workpiece (90-180-270) is almost negligible.

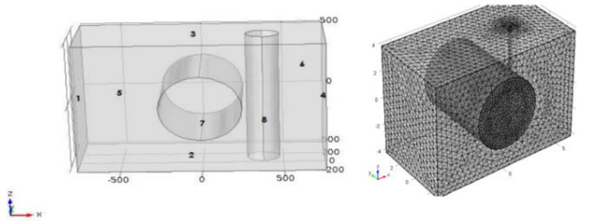

Fig. 6: Isometric view of wire and workpiece along with generated mesh

Fig.8 shows the variation of current density with IEG for same workpiece diameter, while Fig.9 shows the variation of current density for varying workpiece diameter placed at same IEG.

As shown in these figures the variation of current density around the circumference of the workpiece is dependent on diameter and the IEG. It is required to find a relation between the workpiece diameter and minimum inter electrode gap (IEG) for which the current density is concentrated only on the front half circumference of the workpiece. In other words, it is required to find a relation between workpiece diameter and minimum IEG for which the current density at angle 90^0 and 270^0 is less than 0.5 percent of the maximum current density.

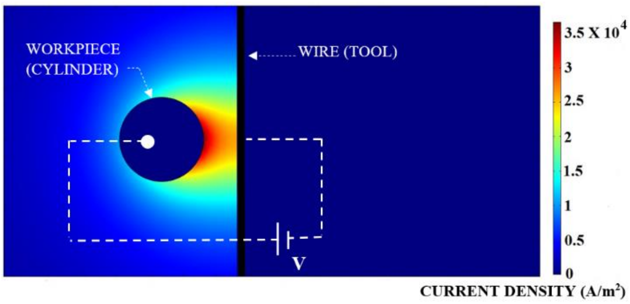

Fig. 7: Variation of current density around the circumference of the workpiece

IEG is found for different workpiece diameters at which the current density at angle 90^0 and 270^0 is less than 0.5 percent of the maximum current density (at angle 180^0). For doing this, workpiece of different diameter is analysed for different inter electrode gap and those combinations which gives current density less than 0.5 percent of the maximum current density at angle of 90^0 and 270^0 of are taken.Other parameters like electrolyte conductivity, applied voltage and dimension of the wire tool are kept constant. One of the results is shown by the Fig.9. These inter electrode gaps are calculated for 16 different workpiece diameters and is listed in table 1.

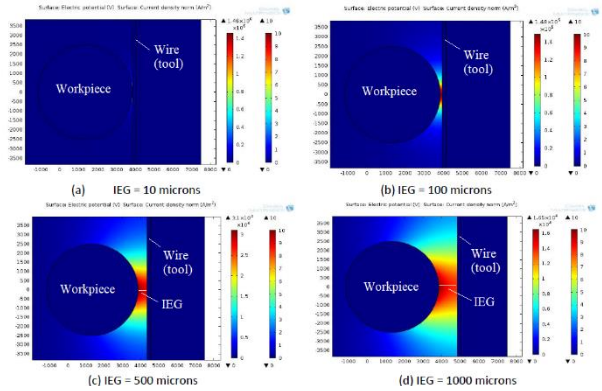

Fig. 8: Variation of current density around the circumference of the workpiece for varying IEG and constant diameter

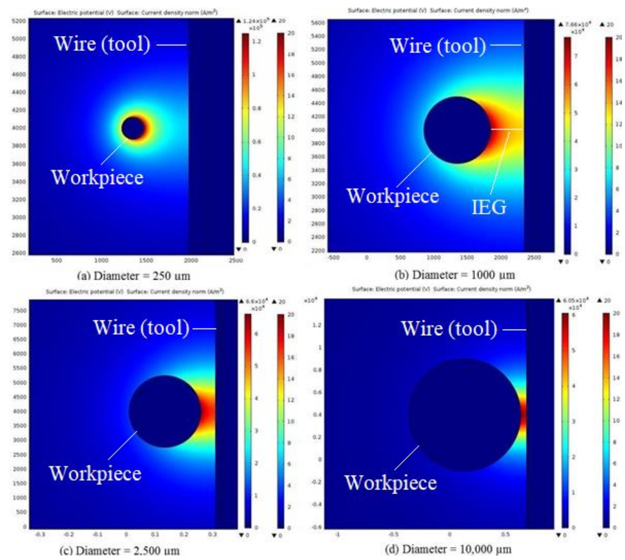

Fig. 9: Variation of current density around the circumference of the workpiece for varying diameter and constant IEG

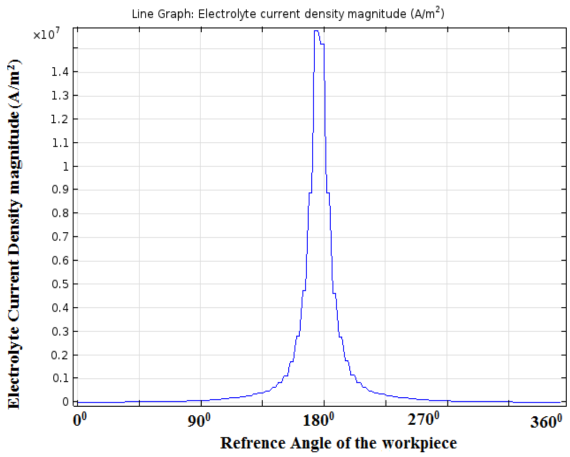

Fig. 10: Variation of current density around the circumference of the workpiece

Table 1: Diameter of the workpiece and the corresponding IEG for which current density at 90^0 and 270^0 is less than 0.5 percent of the maximum current density (at 180^o)

S. No.	Diameter (µm)	Inter electrode gap (µm)
1	50	1.1
2	100	2.2
3	250	5.5
4	500	10
5	750	15
6	1000	25
7	2000	38
8	3000	65
9	4000	90
10	5000	120
11	6000	150
12	7000	180
13	7500	230
14	8000	280
15	9000	300
16	10000	345

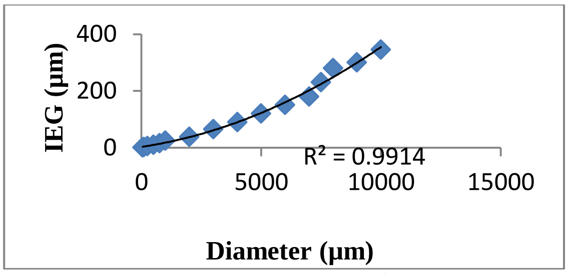

Fig. 11: Regression Curve fitting

Using these results regression curve fitting is done in order to find out the relationship between workpiece diameter and IEG for whichcurrent density at 90^0 and 270^0 is less than 0.5 percent of the maximum current density. The regression equation is as follows:

$IEG = 2 * 10^{-6} D_i^2 + 0.0127 D_i + 3.1985$ ... ***(ii)***

Eq. *(ii)* gives the IEG at which the workpiece of initial diameter D_i should be kept in order to make sure that material is removed from the projected half circumference of workpiece.

Assumption 2: Only the projected length of wire tool takes part in material removal. Also, the curvature of wire tool is neglected.

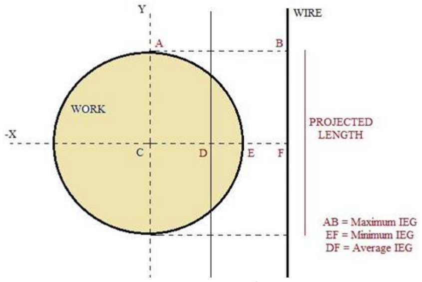

Fig. 12: Schematic diagram of wire and workpiece

Assumption 3: Electrolyte is considered to be incompressible and its conductivity remains constant over the period of experimental run.

Assumption 4: Only surface normal to the cathode undergoes machining i.e., no machining occurs on the side of the normal surface.

3.2 Calculation of mean IEG

From figure 13, the equation of circle (work) with center C can be written as:

$$(x-0)^2 + (y-(b+a))^2 = b^2 \cdots\cdots \quad (1)$$

$$x^2 + (y-c)^2 = 0$$

$$y(x) = c - \sqrt{(b^2 - x^2)}$$

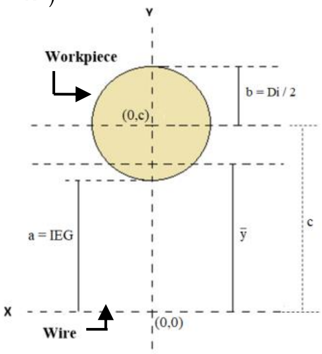

Fig. 13: Calculation of mean IEG

Now, mean inter-electrode gap can be calculated by integrating y(x) from (-b) to (b) and dividing it by 2b.

$$\bar{y} = \frac{1}{2b}\int_{-b}^{b} y(x)dx \cdots\cdots \quad (2)$$

$$\bar{y} = \frac{1}{2b}\int_{-b}^{b}\left(c - \sqrt{(b^2 - x^2)}\right)dx$$

$$\bar{y} = \frac{1}{2b}\left[\int_{-b}^{b} c\,dx - \int_{-b}^{b}(b^2 - x^2)dx\right]$$

$$\bar{y} = \frac{1}{2b}\left\{2bc - \left[\frac{x\sqrt{(b^2 - x^2)}}{2} + \frac{a^2}{2}\sin^{-1}\frac{x}{b}\right]_{-b}^{b}\right\}$$

$$\bar{y} = \frac{2bc - b^2\,\pi/2}{2b}$$

$$\bar{y} = c - \frac{b\pi}{4} \cdots\cdots \quad (3)$$

Substituting the value of c = IEG +D_i/2, in equation (3), we get

$$\bar{y} = IEG + \frac{D_i}{2} - \frac{D_i\pi}{8} \cdots\cdots \quad (4)$$

This mean inter-electrode gap subtends an angle θ at the centre of workpiece (see Fig. 14) and its value can be calculated by substituting the values of IEG and initial diameter in the expression for mean inter-electrode gap.

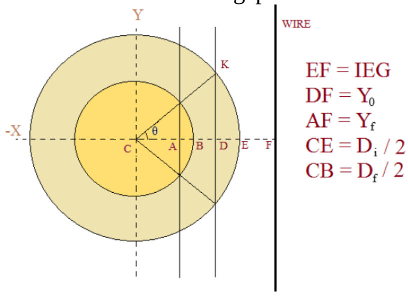

Fig. 14: Calculation of angle θ

Fig.14 shows that workpiece initial diameter (D_i), represented by CE is getting reduced to final diameter (D_f), represented by CB after machining but the angle between the line joining the point of intersection of circle with the line drawn at a distance of mean inter electrode gap from the centre of the circle parallel to y-axis, and x-axis does not change with the diameter.

DE = DF – EF

DE = Mean inter electrode gap – IEG

$$DE = \frac{D_i}{2} - \left(\frac{D_i}{2} - \frac{D_i\pi}{8}\right) = \frac{D_i\pi}{8}$$

Now, CD = CE – DE

$$CD = \frac{D_i\pi}{8}$$

Then, $\cos\theta = \frac{CD}{CK} = \frac{\pi}{4} = 0.785$

Hence, $\theta = 38.278^o$. ….. (5)

Note: θ in the above equation is the angle between the line joining the point of intersection of circle with the line drawn at a distance of mean inter electrode gap from the centre of the circle parallel to y-axis, and x-axis. This angle doesn't depend on the diameter of the workpiece and remains constant with the value of 38.278^0.

3.3 Analytical Modelling

From faraday's first and second law of electrolysis, linear material removal rate can be expressed as:

$$MRR_l = \frac{\eta EI}{F\rho A}$$

$$MRR_l = \frac{\eta EJ}{F\rho}$$

$$MRR_l = \frac{\eta E(V - V_0)k}{F\rho Y_{inst}}$$

$$\frac{dy}{dt} = \frac{\eta E(V - V_0)k}{F\rho Y_{inst}}$$

$$\int_{y_0}^{y_f} y_{inst}\,dy = \frac{\eta E(V - V_0)k}{F\rho}\int_0^t dt$$

$$y_f^{\,2} - y_0^{\,2} = \frac{2\eta E(V - V_0)kt}{F\rho}$$

$$y_f^{\,2} = y_0^{\,2} + \frac{2\eta E(V - V_0)kt}{F\rho}$$

$$y_f = \sqrt{y_0^{\,2} + \frac{2\eta E(V - V_0)kt}{F\rho}}$$

$$y_f = \sqrt{y_0^{\,2} + \frac{2\eta E(V - V_0)kd_w}{F\rho f_{ax}}} \quad ….. \quad (6)$$

From fig. 14, a simple mathematical relation can be written as:

$$y_f + \frac{D_f}{2}\cos\theta = IEG + \frac{D_i}{2}$$

$$\frac{D_f}{2}\cos\theta = IEG + \frac{D_i}{2} - y_f$$

Substituting the expression for y_f from Eq. 6 into the above equation, we get

$$\frac{D_f}{2}\cos\theta = IEG + \frac{D_i}{2} - \sqrt{y_0^{\,2} + \frac{2\eta E(V - V_0)kd_w}{F\rho f_{ax}}}$$

$$\frac{D_f}{2}\cos\theta = IEG + \frac{D_i}{2} - \sqrt{\left(\frac{D_i}{2}(1-\cos\theta) + IEG\right)^2 + \frac{2\eta E(V - V_0)kd_w}{F\rho f_{ax}}}$$

$$D_f = \frac{2}{\cos\theta}\left[IEG + \frac{D_i}{2} - \sqrt{\left(\frac{D_i}{2}(1-\cos\theta) + IEG\right)^2 + \frac{2\eta E(V - V_0)kd_w}{F\rho f_{ax}}}\right]$$

….. (7)

Where, θ is calculated to be 38.278^o. D_i is the initial diameter of the workpiece, D_f is the final diameter of the workpiece, E is the electrochemical equivalent of workpiece, V_o is the over voltage, k is the conductivity of electrolyte, d_w is the wire tool diameter, f_{ax} is the axial feed rate F is faraday's constant (96500 C), ρ is the density of workpiece material.

Note: According to the initial diameter (D_i), the IEG is calculated by the Eq. ***(ii)*** and is fixed initially on the setup before machining starts.

4. EXPERIMENTAL VALIDATION OF MODEL

The model is validated at workpiece rpm of 50. Table 2 shows the tolerance zone of machined workpiece and their respective percentage error. The best relative tolerance obtained is 2.425 %, which suggest that the process of wire electrochemical turning for fabricating micro tools has good repeatability. The best error percentage is 1 %, which suggests that the present model yields good predictions with maximum error of around 6 %. Fig.16 shows micro tool of diameter 205 µm, whose diameter was predicted to be 211 µm by Eq. (7). Machining conditions are as follows:

Voltage = 20V, Electrolyte = $NaNO_3$, 0.25 mol/l, Electrical conductivity = 16.56 mS/cm, Minimum inter electrode gap (IEG) = 94.785 µm (Calculated from expression (*ii*)), Axial feed (of wire tool) = 6.75 µm/min, Workpiece material = Copper.

Table 2: Experimental verification of the model

Final diameter Predicted by model	Actual final diameter	Percent error	Relative tolerance (Tolerance/ Predicted diameter)
4.08 mm	3.94 mm	3.431	2.45 %
	3.95 mm	3.186	
	3.97 mm	2.69	
	4.02 mm	1.50	
	4.04 mm	1.00	
3.71 mm	3.58 mm	3.504	2.425 %
	3.61 mm	2.695	
	3.62 mm	2.425	
	3.66 mm	1.347	
	3.67 mm	1.078	
211 µm	198 µm	6.161	4.265 %
	201 µm	4.739	
	204 µm	3.317	
	205 µm	2.843	
	207 µm	1.895	

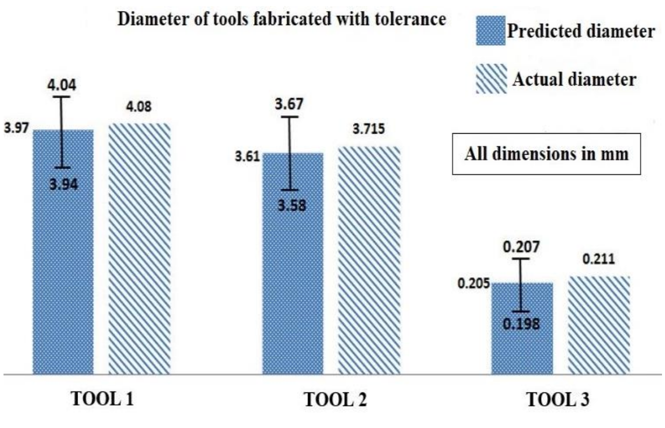

Fig. 15: Experimental validation of the model

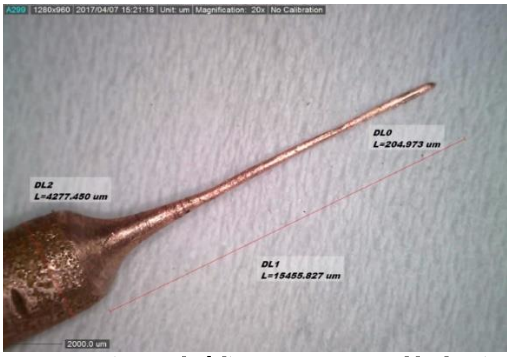

Fig. 16: Copper micro tool of diameter 205 µm and l / d ratio of 75

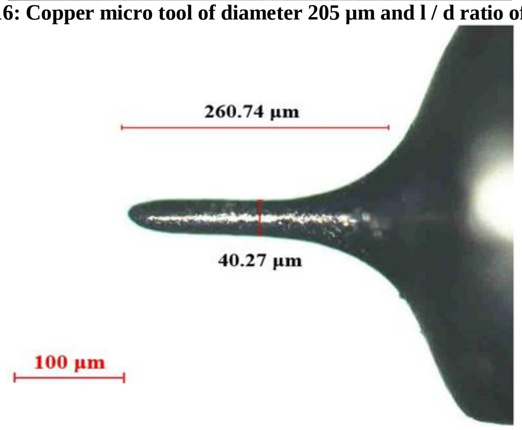

Fig. 17: Stainless steel micro tool of diameter 40 µm and l / d ratio of 6.5

Fig.17 shows micro tool of diameter 40.27 µm, diameter of which was predicted to be 41.83 µm. Machining conditions are as follows:

Voltage = 25V, Electrolyte = $NaNO_3$, 0.50 mol/L, Minimum inter electrode gap (IEG) = 10.00 µm (Calculated from expression (*ii*)), Axial feed (of wire tool) = 2.25 µm/min, Workpiece material = Stainless steel.

5. CONCLUSIONS

1. The process of Wire electrochemical turning is simulated on Comsol Multiphysics software and the distribution of current density over the surface of workpiece is studied for different IEGs and workpiece diameters.
2. From the results of simulations, a quadratic relationship between the minimum IEG and workpiece initial diameter is established for the condition that current density is spread only in the half circumferential region of workpiece. This ensures that at any instant, maximum material is removed from only half circumference of workpiece facing the wire and minimal material is removed from the remaining half circumference.
3. On the basis of faraday's laws of electrolysis and simple geometric relationships, a mathematical model is developed to predict the workpiece final diameter for any given set of working conditions. Agreement of predicted values with experimental results within the error range of 2-5 % signify the genuinity of assumptions.
4. The relative tolerance of parts machined is within 5 %. This indicates good repeatability of wire electrochemical turning process and its suitability in fabrication of microtools.
5. A micro tool of diameter 205 µm and l/d ratio of 75 on copper and of diameter 40.27µm and l/d ratio of 6.5 on stainless steel is successfully fabricated using the results from this model.

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