Journal of Materials Processing Technology 222 (2015) 410–421

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Investigation on profile of microchannel generated by electrochemical micromachining

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ARTICLE INFO

Article history:
Received 2 February 2014
Received in revised form
17 November 2014
Accepted 18 March 2015
Available online 28 March 2015

Keywords:
EMM
Microchannel
Profile
Simulation
Surface roughness

ABSTRACT

Electrochemical micro-micromachining (EMM) is the key micromachining technology for the manufacturing of ultra size components and micro-profiles. Various types of profiles generated by the scanning method and the sinking and milling method with the help of straight, conical and reversed taper micro tool were investigated. Simulation models of different shaped tools are presented and the current density distribution along the side wall and top and bottom surface of workpiece during blind microchannel generation are calculated to predict the shape of cross sectional profile. It was predicted that generation of microchannel with least taper angle of sectional profile was possible with reversed taper micro tool. It was also predicted that generation of microchannel with lesser taper angle of sectional profile was possible with conical micro tool and later on, verified by practical experiments. The major process parameters investigated were electrolyte concentration, front end shape of micro tool and vibration of micro tool on surface finish. Taper angle of microchannel generated by the sinking and milling method is always lesser than that of microchannel generated by the scanning machining layer by layer method. Cross sectional profile generated by reversed taper micro tool will have the tendency to be least tapered or without taper depending on reversed taper angle of the micro tool. Taper angle of blind microchannel generated by the 2° reversed taper micro tool was 17° which is considerably lower than 25° observed in the case of profile generated by straight micro tool. During the generation of blind microchannel by conical micro tool, taper angle of cross sectional profile decreases with the decrease in taper angle of micro tool generating the profile i.e. 14.5° taper angle of profile generated by conical micro tool having 10.5° taper angle and 5.14° taper angle of profile generated by conical micro tool having 4.34° taper angle.

1. Introduction

Micro machining technology is progressing rapidly in the field of micro fabrication of micro devices used in communication, electronics, micro fluidics, MEMS and computer industry. The demand for micro parts in the above mentioned fields are very high as there is a trend in the society to have microproducts due to limitation of space, energy and material etc. One of the well known micromachining technology is the lithographic process used extensively for silicon machining. The material properties of silicon do not suit the requirement of micro surgery, biotechnology and high strength application at higher temperature. Micro EDM technology has also been used for the generation of microgrooves and micro holes etc. in electrically conductive advanced materials but inherent problem is heat affected zone in the work piece. There are specific advantages of Electrochemical micro-micromachining (EMM) over the other micro-machining techniques such as no heat affected zone, stress free smooth machined surface, machining capability of all advanced metals irrespective of hardness of material, no burr, no tool wear etc. EMM can be used for the micro fabrication of stainless steel for the possibility of wide application in the area of surgery, micro reactors, biotechnology etc. Lee et al. (2002) generated microgrooves with the variation of depth identified by machining current and inter-electrode gap size, on the air lubricated hydrodynamic bearing and thereby improving the possibility of wider use of microchannels or micro profiles in the high speed gas or air lubricated bearing. Bhattacharyya and Munda (2003) developed EMM set up and studied influence of machining process parameters on machining criteria such as material removal rate (MRR) and overcut phenomena. Li et al. (2003) applied side insulated tool to drill micro-hole using pulsed voltage and the improvement of machining accuracy was shown. Ahn et al. (2004) drilled micro holes on stainless steel plate using nanosecond pulses in H_2SO_4 electrolyte by fabricated tungsten carbide tools.

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http://dx.doi.org/10.1016/j.jmatprotec.2015.03.025
0924-0136/

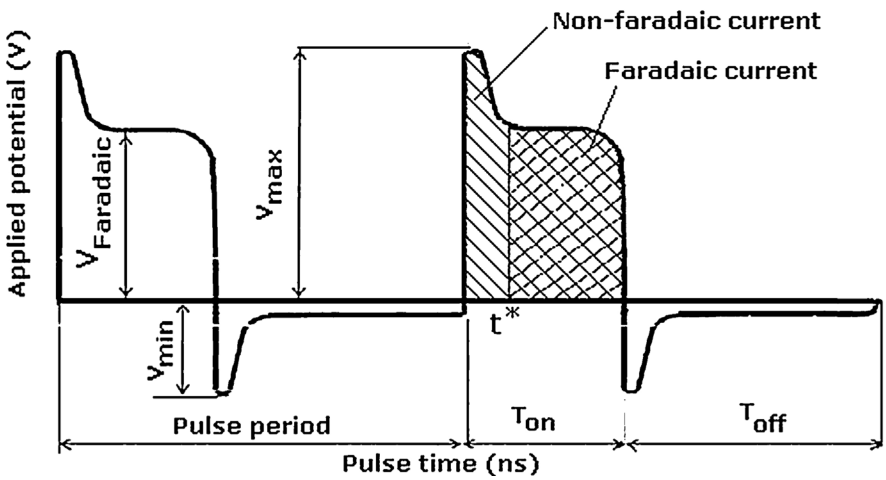

Fig. 1. Charging and discharging waveform during pulsed EMM.

Kozak et al. (2008) conducted EMM using ultra short (nanoseconds) pulses and presented a mathematical model of micro-shaping process, taking into consideration the unsteady phenomena in double layer. Kim et al. (2005) proposed taper reduction technique with disk type electrode and multi-holes were drilled at a single step in H_2SO_4 electrolyte. Ryu (2009) used citric acid as environment friendly electrolyte for the generation of micro square cavity and micro circular cavity on stainless steel. Schuster et al. (2000) used ultra short pulse voltage experimentally to fabricate an ultra size copper structure and copper tongue based on the finite time constant for double layer charging. Kirchner et al. (2001) fabricated three dimensional micro elements on stainless steel by applying nanosecond voltage pulses using a mixed electrolyte of HF and HCL. Hewidy et al. (2007) improved accuracy in ECM with the application of low frequency vibrations of tool and presented a model. Yang et al. (2009) used ultrasonic vibration of semi-cylindrical tool for the drilling of deep holes with reduced machining time and machining gap. Pattavanitch et al. (2010) applied boundary element method to model the slot milling by electrochemical machining and presented a 3D model with the discretized domain of the work piece and tool surfaces. Purcar et al. (2004) presented simulation model of 3D anodic shape change during electrochemical machining based on “marker” method. The work piece shape change was found by displacing each node proportional with, and in the direction of current density. Hocheng et al. (2003) presented a theoretical and computational model on the evolution of profile with the elapse of time while φ 100 μm holes were being machined by electrochemical machining. Wang et al. (2010) presented a simulation model and finite element based solution of current density distribution for predicting the shape evolution during through-mask EMM of surface patterning. Donglin et al. (2011) presented a mathematical model describing the EMM using inert metal mask (platinum plate) and simulation of shape evolution. Ghoshal and Bhattacharyya (2014) simulated machining zones with reversed taper tool and conical tool during EMM of microhole and predicted that both reversed taper and forward taper tool could be used for generation of taper less micro holes. Some of the above mentioned researchers dealt with shape evolution during drilling operation and very few described about the shape evolution during generation of microchannel. Moreover, all the shaping models reported by the researchers are related to straight tools only.

The cross sectional profile is an important attribute of microchannel from the point of view of application in micro fluidics, biomedical and engineering sector. Other attributes that define the electrochemical micromachining qualities of microchannel are size, overcut, taper angle and surface finish. In the present work, emphasis has been given to reduce taper angle of cross sectional profiles, produce good quality of surface and generate various shapes of micro-profile by the use of straight, conical and reversed taper micro tool during EMM. The major process parameters investigated were electrolyte concentration, vibration of micro tool and front end shape of micro tool on the two methods of blind microchannel generation i.e. the scanning machining layer by layer method (Malapati and Bhattacharyya, 2011) and the sinking and milling method (Ghoshal and Bhattacharyya, 2013).

2. Simulation models of machining zone with different shaped tools

Anode and cathode separated by a very narrow gap and having appropriate electrolyte between the electrodes results in the dissolution of anode and the shape generated depends on the current density distribution at the vicinity of anode surface which is going to be dissolved. In the case of pulsed power supply, there is pulse on time, T_{on} and pulse off time, T_{off} during each cycle as shown in Fig. 1. In electrochemical micromachining, the total current supplied during a pulse period is the sum of faradaic current and nonfaradaic current (Mithu et al., 2012). At the very beginning of the pulse, instantaneous voltage is V_{max} while whole current is used for the time t^* to charge the double layer capacitance without dissolution of metal and this current is called nonfaradaic current. While the double layer is being charged, the potential drops due to overpotential and after the proper charging of double layer, voltage becomes flat ($V_{Faradaic}$), and faradaic current flows throughout the rest of pulse on time resulting in dissolution of anodic metal. The double layer is discharged completely by applying slightly negative voltage to avoid DC current and thereby, advantage of pulsed voltage such as localization of dissolution in EMM is utilized fully.

For the purpose of analysis of electric field in the inter-electrode gap (IEG), two dimensional model of analysis is adopted for the sake of simplicity. Mathematically, according to Faraday’s two laws of electrolysis, amount of material dissolved per unit time is given by

$$\frac{dm}{dt} = \frac{\eta i M}{zF} \tag{1}$$

where m is mass dissolved, t is time in s, i is current in amperes, M is molecular mass, z is valency of anodic metal and F is Faraday constant. The current efficiency, η is defined as the ratio of the actual amount of metal dissolved to the theoretical amount as predicted by Faraday’s laws of electrolysis.

Let s be the recession of anodic metal in the perpendicular direction of elemental area where current density is J and ρ is the density