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Vibration assisted electrochemical micromachining of high aspect ratio micro features

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ABSTRACT

The most used processes for generation of high aspect ratio microchannels are Nd: YAG laser technology on silica substrate and ultra violate lithography (UV-LIGA) process on metals. There are a few micromachining technologies such as micro mechanical milling, micro electro discharge machining (EDM) and electrochemical micromachining (EMM) for production of high-aspect-ratio micro features on highly stressed and anticorrosive metal like stainless steel. This paper discusses the micro fabrication of high aspect ratio micro features at the intended location on high strength stainless steel sheet of very small thickness to high thickness with highest average aspect ratio 14.33 achieved during microchannel generation by EMM with the help of coated microtool. Mathematical model relating aspect ratio with various parameters and machining conditions is derived to explore the ways to increase the aspect ratio of micro features. Experimental investigations were carried out to know the effect of vibration of microtool, frequency of pulsed voltage, microtool tip shape, thickness of work piece and non-conducting layer coated microtool on high aspect ratio micro features. Vibration of microtool with very small amplitude improved the stability of micromachining due to improved flow of electrolyte.

1. Introduction

Development of micromachining technologies are crucial to meet the requirement of micro-technology based products like microchip, switches, printed circuit board, micro sensors, chemical micro-reactors, stress free micro holes and slots in aerospace industry, micro fuel injection nozzles in automotive engines, biomedical, micro-fluidic systems like inkjet printers and micro-electromechanical systems etc. Micro products have gained recognition in societies due to easy handling and accommodation in limited space. Moreover, micromachining technologies help in saving material, energy while incorporating improved functionalities within limited space. Micro grooves of width of less than 50 μm with an aspect ratio of 3 on brass and micro grooves of 100 μm width on stainless steel with an aspect ratio of one have been cut reportedly by micro end mills which were fabricated by grinding. Subsequent electrochemical polishing was required [1]. One of the disadvantages was easy breaking of microtools during the grinding process. Moreover, to avoid poor surface finish and remove burrs subsequent electrochemical polishing was required. Microchannels of high aspect ratio have been fabricated reportedly by micro EDM, electron beam machining (EBM), and laser beam machining (LBM). These non-conventional machining processes are based on thermal energy and hence, thermal distortion of the machined surface with heat affected zone, surface cracks and residual stresses in the work piece are common disadvantages. 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, high material removal rate (MRR), better surface finish, no burr and no tool wear etc. Micro features are essential parts of micro-sensors, chemical micro-reactors, micro-fluidic systems, heat exchangers of computer chips and numerous MEMS applications. A mathematical model of micro electrochemical milling by layer was established theoretically and experimentally where, it was concluded that milling layer thickness should be less than cylindrical electrode diameter for good shape precision. 2D and 3D complex micro structures were also machined by micro electrochemical milling by layer process by using in situ fabricated cylindrical electrode [2]. This is not always the fact proven in the case of layer by layer scanning machining method where milling layer thickness is very small still

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both ends of microchannel are of oversize. Moreover, overcut of microchannel is bound to be higher if horizontal feed rate is same as vertical feed rate. Micro groove of 50 μm width, 300 μm length, 110 μm depth and aspect ratio of 2.2 was machined on stainless steel by micro electrochemical milling using disc type electrode to reduce taper. WC disc-type electrode of disc diameter 54 μm, neck diameter 22 μm and height of disc 10 μm was made by micro EDM [3]. Through, as well as blind microchannels were generated on copper foil by layer by layer scanning machining method [4]. Overcut or side gap is higher in this method. Taper reduction technique was explained with a WC disk-type electrode of disk diameter 54 μm and 22 μm neck diameter made by micro EDM during stainless steel machining. A micro column of 20 μm width, 40 μm length and 85 μm height was fabricated on SS-304 sheet. Aspect ratio of the column was about 4.25 [5]. Microchannels were generated by a new approach of sinking and milling method in EMM where, microtool moves vertically to final depth or required depth of machined feature followed by milling along the path of the micro features. It was also established that sinking and milling method of micro profile generation by using cylindrical microtool in EMM was better in terms of reduced taper angle, overcut, edge deviation and time of machining [6]. A novel method for fabricating high aspect ratio microstructure by EMM using slight vibration of tungsten wire with the frequency of 5 Hz was employed where, micro wire electrode moved towards the thick work piece from one of the edges while electrolyte flowed through the wire electrode. Micro groove with the width of 15 μm and aspect ratio 10 was machined experimentally [7]. One of disadvantage of this method is micro groove cannot be machined at the intended location without starting from edge. A nickel based microchannel cooling plate with channels of width 20 μm and aspect ratio 3.6 was fabricated using a modified UV-LIGA technique in a single electroplating step. An electroplated copper was also fabricated with channels of width 15 μm and aspect ratio up to 5 [8]. A Femtosecond laser was used to fabricate microchannels in glass with high aspect ratios by laser direct ablation process [9]. Investigation on shape, size, surface quality and elemental characterization of blind micro holes of aspect-ratio 7 was carried out in die sinking micro EDM [10]. Micro holes were drilled on stainless steel sheet using ultra-short pulses with tens of nanosecond duration in H_2SO_4 electrolyte with fabricated tungsten carbide tools. Through hole of φ 13.6 μm entrance, φ 10.5 μm exit was drilled on 100 μm thickness stainless steel foil. Thus, aspect ratio of 8.29 was achieved for one dimensional (Z direction) movement of microtool [11]. Effect of tool diameter, length and applied pulse frequency on the shape and size of the fabricated micro-holes and MRR have been investigated along with illustrations of charging and discharging waveforms [12].

EMM of high aspect ratio is a challenging task before the researchers. From the previous researches it is clear that moderate aspect ratio micro features have been machined. In many cases, only Z directional tool movement was involved for generation of high aspect ratio microhole. This paper discusses the micro fabrication of high aspect ratio micro features by EMM at the intended location on high strength stainless steel with two dimensional tool movements. In the case of generation of high aspect ratio microchannel complicacy arises particularly, for a high depth machining due to difficulty in availability of fresh electrolyte into extremely narrow gap in the machining zone. In this paper, in depth studies have been carried out on SS-304 sheet of very small thickness to high thickness to achieve highest aspect ratio during microchannel generation with the help of coated microtool. Experimental study of process parameters such as vibration of microtool, frequency of pulsed voltage, microtool tip shape, thickness of work piece, machining time and depth of sinking by microtool have been conducted for the investigation and analysis of their effects on material dissolution during machining of high aspect ratio holes and microchannel by EMM utilizing sinking and milling method. This research aims at manufacturing of high-aspect-ratio micro features for micro components based on EMM in terms of reduced overcut and time of machining. Proper methodology of EMM has been recommended to overcome the difficulties in EMM to achieve high aspect ratio.

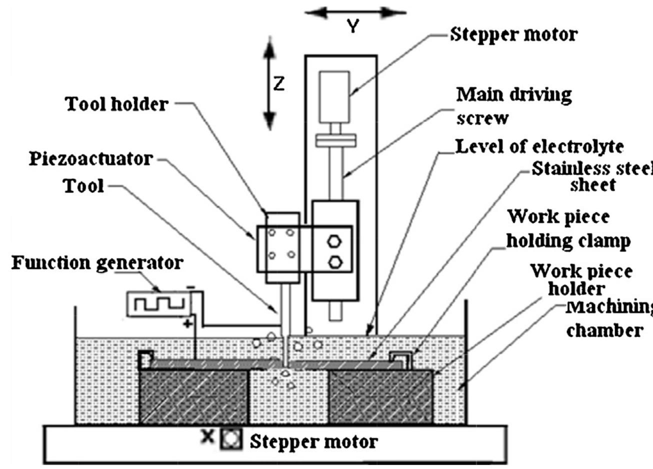

Fig. 1. Schematic diagram of EMM.

2. Principle of EMM with vibrating electrode

EMM is an anodic dissolution of metal by electrochemical reaction where, anodic work piece and cathode tool are separated by an appropriate electrolyte and pulsed power is applied for better localization of current. Fig. 1 shows the schematic view of EMM. Current passes through the narrow gap of 5–20 μm between microtool and work piece. Function generator is used to create pulse power. Motion of work piece or microtool are actuated by stepper motors and controlled by software. Electrochemical micromachining (EMM) is performed with ultra short pulse. Electrolyte resistance is the product of gap distance between electrodes, S and the specific electrolyte resistivity, $\rho_{S.}$ The charging time constant (τ) for the double layer of specific capacitance ($C_{\rm dl}$) is $\tau = \rho_S \times C_{\rm dl} \times S$. If the duration of pulse (on time) is longer than the charging time constant for a machining zone of IEG (S), the double layer is charged enough for dissolution of metal. The regions of higher IEG for which τ is obviously greater than pulse duration are not dissolved due to insufficient charging of double layer.

Mathematically, according to Faraday's two laws of electrolysis and Ohm's law, volume of material dissolved is given by

$$V_m = \frac{K\,EAt}{S\,\rho_s} \tag{1}$$

where A is the active anode area and S is the inter-electrode gap (IEG), E is the voltage value acquired by oscilloscope, t is the time of machining, K is the electrochemical constant and is given by $K = M/\boldsymbol{Z} \times F \times \rho$ for a particular material, where, M is molecular mass, Z is valency of anodic metal, F is Faraday constant and ρ is the density of anodic metal. During each cycle of pulsed power proper charging of double layer is must before dissolution current starts flowing across double layer during faradaic time.

$$\text{Faradaic time for each cycle is given by } T_{\rm on} - \tau \tag{2}$$