FABRICATION OF DISC SHAPED MICROTOOL BY ELECTROCHEMICAL MICROMACHINING FOR MICROMACHINING APPLICATIONS

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Abstract

Electrochemical micromachining (EMM) is widely used for micromachining applications due to its various benefits over other micromachining methods. Microtool is the vital element in EMM, since the features of the microtool like shape, size and surface finish are directly transferred to the work surfaces affecting its machining accuracy and surface quality. Disc shaped microtools are useful to improve the machining accuracy in terms of reduced overcut, taper angle and stray current effects in EMM. Disc microtools fabricated by different machining techniques need separate machine setup and includes microtool handling, increasing the risk of microtool damage. This paper presents the micro machining techniques to fabricate the disc shaped microtools of different shank diameters, disc diameters and different disc heights with improved surface quality as required for micromachining applications, from tungsten microrod by EMM. Finally, disc shaped microtool of disc $\Phi$175 µm, disc height 70 µm and shank $\Phi$93 µm was fabricated from tungsten microrod of $\Phi$300 µm and used to machine the micro features like straight cylindrical microhole, straight walled microgroove and 3D micro structures on stainless steel by EMM.

Keyword: Electrochemical micromachining, Disc shape microtool, shank diameter, disc diameter, disc height.

1. Introduction

Increasing demands for compact and multifunctional devices have originated global competition among the manufacturing industries and forcing them to reduce the size of the industrial and household products. Multiple benefits of the microporoducts such as improved multi-functions, less required space, low energy consumption, and low production cost, have also attracted industries to use microporoducts in various fields. Therefore, there is always a need to search suitable micromachining techniques, to machine the micro features on the micro devices made of advance engineering materials. Electrochemical micromachining (EMM) is one of the best micromachining techniques due to its several benefits over other micro machining methods, which includes no tool wear, stress-and-crack free surface, good surface finish, and importantly any metallic surfaces can be machined irrespective of its hardness[Bhattacharyya et al. (2002)]. Microelectrode as the tool in EMM, is an important element in the machining of micro features, since the features of the microtool like shape, size and surface finish are directly transferred to the workpiece. Hence, precise microtools with good surface finish are preferred in machining of micro features [Rathod et al. (2013)].Straight cylindrical microtools of different diameters can be developed by EMM, regulating machining voltage, machining time and current density [Liu et al. (2011), Jain et al. (2012)] and also be used for machining of complex structures by EMM [Liu et al. (2012)].Microtools with uniform diameter can be fabricated by electrochemical machining in very short time, with 2 V to higher voltages by vibrating microtool with suitable amplitude, during machining of microtool[Ghosal and Bhattacharyya (2013)]. In EMM, tapers are formed along the walls of micro features due to the machining time difference, during machining with straight cylindrical or conical micro tools. Disc shaped microtool are useful to minimize the taper as well as overcut, by restricting the dissolution of the workpiece material along the disc height only [Kim et al. (2005)]. Microelectrodes of different end shapes can be fabricated by reverse electro-discharge machining method and used for micromachining applications [Jiwang et al. (2010), Kim et. al. (2006)].Microtool of complex shapes can also be fabricated by localized electrochemical deposition method and by electro-discharge machining block electrode method [Habib et al. (2009), Nachiappan et al. (2002)]. Disc
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Microtools fabricated by reverse Electro-Discharge Machining or Wire Electro-Discharge Grinding method, generate poor surface quality of the microtool, needs separate machining setup, which includes microtool handling, increasing the risk of microtool damage during handling, thereby reducing production rate and increasing machining cost.

This paper presents the machining techniques to fabricate the disc shaped microtools of different shank diameters, disc diameters, and disc heights with improved surface quality, from tungsten microrod by EMM, thereby eliminating the need of separate machine setup to fabricate disc microtool, which minimizes microtool handling in micromachining applications. Fabricated disc shaped microtool have been used to machine the micro features like straight cylindrical microhole, straight walled microgroove and 3D microstructures on stainless steel by EMM.

2. Experimental Details
2.1 Working Principle
Disc microtools were fabricated by reverse EMM, in which tungsten microrod as anode and SS plate with central hole as cathode was connected to power supply and immersed in an electrolyte. Low voltage pulsed DC supply applied to anode and cathode, results anodic dissolution of tungsten microrod to give desired dimensions of the microtool. Top and bottom surface of the SS plate were insulated so that only inner wall of the central hole remains current carrying part. Tungsten microrod insulated at the front end and positioned at the central hole of the plate as shown in fig. 1. During machining, material dissolved from the microrod to get the desired shank diameter, finally insulation was removed and disc was finished to get desired disc dimensions.

When machining current is applied between the electrodes, electrochemical reactions takes place at anode and cathode which can be described as:

At anode: \( W + 8OH^- \rightarrow WO_4^{2-} + 4H_2O + 6e^- \)

At cathode: \( 6H_2O + 6e^- \rightarrow 3H_2↑ + 6OH^- \)

At anode, tungsten reacts with hydroxide ion and dissolves into electrolyte in the form of tungsten ion. Whereas at cathode, water molecule is divided into hydrogen ion and hydroxide ion, and hydrogen ion is converted into hydrogen gas, after gaining an electron. The generated hydrogen gas forms bubble and emerges from the surface of cathode. At anode surface, tungsten ions are released into electrolyte and moves away by diffusion and migration. At higher applied voltage, dissolution rate is higher than diffusion rate of tungsten ion and forms a thin layer around the microtool surface, called as diffusion layer. Diffusion layer obstructs the movement of hydroxide ions from bulk electrolyte solution to the microrod surface, hence local dissolution rate decreases in inverse proportion to the thickness of diffusion layer. Particles of diffusion layer moves downwards along the microrod surface by gravity. This downward flow makes the layer thicker at the bottom end of the rod and thinner at the shank end, resulting reverse conical shape at shank of the tool. Non uniform thickness of the diffusion layer affects the electric field distribution during the reaction and the final shape of the microtool. Since the effect of diffusion layer varies with electrochemical dissolution conditions, final shape of the disc microtool can be controlled by varying the machining parameters like applied voltage, pulse frequency, duty ratio, electrolyte concentration, and machining time. Therefore by controlling machining parameters, disc microtool of desired dimensions can be obtained. Finally, insulation was removed from the front end of the microtool and processed for the required disc height.

![Fig. 1. Fabricating principle of disc microtool](image)

2.2 Experimental Setup
Experimental setup used for fabrication of disc microtool and machining of microfeatures using developed disc microtool by EMM, consists of various subsystems namely mechanical machining unit, controller unit, desktop computer, power supply, digital storage oscilloscope, measuring microscope and machining chamber with work holding arrangement etc. Mechanical machining unit provides basic movements to the microtool/workpiece through the long travel linear stages representing X, Y, and Z axis. It also has base to mount the machining chamber and an arrangement to hold microtool holder. Machine controller unit regulates the movement of linear stages through desktop computer by simple programs. Power supply provides pulsed DC supply and digital storage oscilloscope online monitors the supplied pulses during machining.
Fabricated disc microtools and machined microfeatures were observed through stereozoom microscope and measured using measuring microscope.

2.3 Experimental Plan
Tungsten microtool specimens about 15 mm each were cut from straight cylindrical microrod of $\Phi 300 \mu m$. Ends of each specimen were ground, fine finished and inspected under observing microscope for surface cracks and end defects, if any. Finished specimens were mounted on microtool holder. Experiments were systematically planned to fabricate disc microtools of different shank diameters, disc diameters and disc heights by regulating the EMM process parameters like applied voltage, duty ratio, machining time and insulation length at the front end of the tool specimen. Fabricated disc shaped microtools were measured and analyzed for the dimensional accuracy. Fig. 2 illustrates the measurement strategy for fabricated disc shaped microtool. Fabricated disc microtools were then used for machining of different microfeatures on SS by EMM.

3. Results and Discussions
Disc microtools of smaller disc heights are preferred in EMM to reduce taper angle, overcut and stray current effects in machined microstructure. To fabricate taper-free micro features using disc microtool, radial difference between disc diameter and shank diameter must be greater than the difference between the machining gap at the top and bottom surfaces of machined microfeature. Hence, various combinations of shank diameters and disc diameters are required for machining of different microfeatures of varied sizes by EMM, which necessitate fabrication of disc microtools of different dimensions. Machining techniques to fabricate disc microtools of different shank diameter, disc diameter, and disc height with improved surface quality from tungsten specimen, by EMM are discussed below:

3.1 Fabrication of disc microtool of different shank diameter
Disc shaped microtools of uniform shank diameters can be fabricated by regulating the material dissolution rate at appropriate machining parameters such as applied voltage, pulse frequency, duty ratio, and electrolyte concentration, and by controlling machining time. Microtool specimen with front end insulation was machined for 15 minutes and shank diameters were measured at fixed time intervals to investigate the influence of machining time over the shank diameter. The machining parameters were as applied voltage 1V, pulse frequency 1MHz, 80% duty ratio, 1M NaOH electrolyte. Shank diameters were measured at fixed time interval of 2 minutes each after 5 minutes of machining time. Fig.3 plots the variation in shank diameters with respect to machining time. From graph it can be seen that, shank diameter decreases with increase in machining time, since the dissolution of the material continues from shank surface with machining time. Microscopic images of microtool showing variations in shank diameters with machining time are shown in fig. 4 a-e. Front end insulation was removed finally to get disc microtool of desired dimensions as shown in fig. 4f. This proved the possibility of fabricating disc shaped microtools of desired shank diameter by regulating machining time at proper parametric combinations like applied voltage, pulse frequency, duty ratio, and electrolyte concentration.

3.2 Fabrication of disc microtool of different disc diameter
Disc microtools of uniform disc diameters can be fabricated by regulating the material dissolution rate at appropriate machining parameters such as applied voltage, pulse frequency, duty ratio, and electrolyte concentration, and by controlling machining time. Microtool specimen with front end insulation was machined for 5 minutes and disc diameters were measured at fixed time intervals to investigate the influence of machining time over the disc diameter. The machining parameters were as applied voltage 1V, pulse frequency 1MHz, 80% duty ratio, 1M NaOH electrolyte. Disc diameters were measured at fixed time interval of 2 minutes each after 5 minutes of machining time. Fig.5 shows surface qualities at disc surfaces of disc microtool before machining and after 15 min. of machining time. Increased dissolution time reduces shank diameter which also minimizes difference between peaks and valleys on shank surface, and further material dissolution from reduced surface area improves uniformity in material dissolution around the shank diameter. Hence, shank surface quality improves with...
reduction in shank diameter with increase in machining time.

Fig. 4 Shank dia. at machining time of a. start b.5min c. 9 min d. 13min e. 15min f. finished disc microtool

Fig. 5 Surface quality of shank at a. start b. 15 min.

3.2 Fabrication of disc microtool of different disc diameters
Disc microtools having smaller disc diameters are preferred to machine microfeatures with better machining accuracy in EMM, for micromachining applications. However, different combinations of disc diameters and shank diameters are required to machine the taper-free micro features by EMM, which necessitates fabricating disc microtools of different dimensions. Disc microtools of required disc diameters can be also be fabricated by EMM in two steps. In first step, tungsten microtool specimen without insulation was machined to straight cylindrical microrod of required disc diameter. In second step, insulation was applied at front end and machining continued to get the required shank diameter.

Fig. 6 depicts the fabrication steps in disc shaped microtool of disc diameter 175 µm, disc height 70 µm and shank diameter 93 µm fabricated from tungsten specimen of φ300 µm. In first step, straight cylindrical tungsten specimen of as shown in fig. 6a was machined to straight cylindrical microrod of 175 µm and in second step, insulation was applied at front end of microrod as shown in fig. 6bandby further continuation of machining, disc shaped microtool of shank diameter 93 µm is obtained as shown in fig. 6c The machining parameters in both steps of machining were applied voltage of 1 V, pulse frequency 1 MHz, duty ratio 80% and electrolyte concentration of 1M NaOH.

Fig. 6a. bare microrod b. machined cylindrical microrod c. disc microtool
3.3 Fabrication of disc tool of different disc heights
In electrochemical micromachining of microfeatures using disc microtools, disc height plays an important role in machining accuracy, since the dissolution of the workpiece material is restricted to the disc height region only. Therefore, disc microtools with minimum disc heights are preferred while machining of accurate microfeatures. Disc microtools with different disc heights can be fabricated by varying the length of insulation applied at the front ends of the microtool specimens, during fabrication. Front ends of the specimens were insulated with different insulation lengths and machined with applied voltage of 1 V, pulse frequency of 1 MHz, with 80% duty ratio and 1 M NaOH electrolyte, to get the different disc heights of disc microtool.

Fig. 7 Disc heights with insulation length
Fig. 7 plots the variations in disc height with respect to the front end insulation length. During electrochemical machining of microtool, radius of curvature is generated at both sides of the shank because of surface tension of electrolyte at upper side and due to continuous reduction in shank diameter during machining at lower side of the shank, hence generated disc height remains always smaller than the insulation length.

Fig.8a-d shows the microscopic images of the fabricated disc microtools of different disc heights, proving the possibility of fabricating the disc microtool of different disc heights with different shank diameters by controlling the insulating length and machining time in EMM.

Fig. 9 a. St. cylindrical microhole b. St. microgroove
Fig.10 3D microstructure with plane surfaces

4. Machining of Microfeatures by EMM
Various micro features like straight cylindrical microhole, microgroove and 3D microstructure, were machined using developed disc microtool by EMM. Fig. 9 a. shows the microscopic image of entry and exit sides of the cylindrical microhole machined with applied voltage of 2.8 V, pulse frequency of 5 MHz, dilute sulphuric acid of 0.2 M NaOH as an electrolyte, tool feed rate of 0.11 μm/s, and 35% duty ratio on SS sheet of
390 µm thickness. Very less diametric difference between entry and exit side diameters makes it nearly straight cylindrical microhole generated using disc microtool. Fig. 9 b. shows the straight walled microgroove of 1500 µm length, with negligible stray current effects and fig. 10 shows 3D microstructure with plane surfaces machined on SS sheet of 390 µm thicknesses, respectively. Layer-by-layer machining strategy for microtool movement was adopted during machining of microgroove, and 3D microstructure, with applied voltage of 2.8 V, pulse frequency 5 MHz, duty ratio 40% in 0.15 M H₂SO₄ as an electrolyte. Path for the disc microtool movement was programmed with few microns of initial inter-electrode gap. Microtool moved with scanning speed of 93.75µm/s with vertical tool feed of 0.625 µm at the end of each scan. Straight walls of the microstructure with no stray current effects on the top face results improved machining accuracy and surface quality by using disc shaped microtool.

5. Conclusions
Disc microtools of varied dimensions were fabricated from tungsten microrod by EMM and fabricated disc microtools were used to machine the micro features on stainless steel. Following conclusions can be summarized while fabricating disc microtools by EMM:
(i) Thickness of diffusion layer plays an important role in generation of uniform cylindrical shank diameters. Diffusion layer thickness can be controlled by controlling dissolution rate i.e. applied voltage and machining time while fabricating disc microtools.
(ii) Shank diameters of disc microtools can be controlled by regulating the machining time with appropriate process parameters. Shank diameter decreases with machining time with improved surface quality.
(iii) Disc microtools having different disc diameters with improved surface quality can also be fabricated by machining microrod in multiple steps.
(iv) Front end insulation of the microtool plays an important role in fabrication of different disc heights of the disc microtool. Lower disc heights are preferred for better accuracy in EMM.
(v) Fabricated disc microtool have been used successfully to machine the straight walled microfeatures like straight cylindrical microhole, microgroove and 3D structures with plane surfaces on SS by EMM.
High aspect ratio micro features are required on various microproducts for its practical applications. Machining of these micro features by EMM necessitates the disc microtools with minimum disc height and smaller shank diameter. Therefore, further developments in fabrication of disc microtools with smaller disc height and smaller shank diameter are needed for its practical application in the field of micromachining.

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