Influence of Wire Feed Rate in WECM during Fabrication of Microfeatures

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Abstract

In today's world, miniaturization of products has become a prime need and modern fabricators are tending towards application of suitable techniques for downsizing of components to achieve better usability and functionability by overcoming both space limitation and product space restriction. The fabrication techniques adopted by modern manufacturing industries are quite capable of generating microfeatures with desired geometries and requirements. But with further technological advancements and requirement of intricate 3D and high aspect ratio micro structures, a new kind of micromachining process is being applied. This newly developed and implemented technique, known as wire electrochemical machining (WECM) process has added advantages and can precisely fabricate features within micron ranges by removing the excess material electrochemically. However, the process is still at its infant stage and very little is known about the process characteristics, capability and applicability. Hence, the present research work deals with the development of suitable WECM setup for fabrication of microfeatures with desired criteria. Also, attempts has been made to find out the effect of controllable parameter such as wire feed rate, particularly at higher ranges, on corresponding slit width of the generated microfeatures. For this, experimentations have been carried out with 50 µm tungsten wire on 100 µm stainless steel (SS304) workpiece and after the experiments the machined microfeatures have been carefully observed under optical microscope to obtain required measurement data. Additionally, the experimental results have been represented graphically to get a further insight about the influence of wire feed rate on required output criteria where the minimum average width of the microslit achieved is 86.7 µm with an aspect ratio of 1.15. Moreover, complex microfeature with varying width has been fabricated by changing corresponding feed values during single run in order to explore the process capability.

Keywords: Wire electrochemical machining (WECM) process, wire feed rate, microslits, slit width.

1. INTRODUCTION

With rapid modernization in different fields such as automotive, aerospace, electronics, medical and optics, fabrication of complex micro structure and features are becoming very important. To cope up with the growing market demands in producing various intricate micro products, modern fabricators are adopting suitable micromachining techniques to remove surplus material and for achieving desired shape within micron ranges. Based upon the functionality and applicability, all these micromachining processes have unique mod of material removal and have their own merits and demerits. But, with further technological development and increasing requirement for precise high aspect ratio microfeatures, a new type of micromachining process has recently been introduced. This process, being known as Wire Electrochemical Machining (WECM) has added advantages than preexisting Electrochemical Micromachining (EMM) process and can readily machine complicate 3D micro features with desired geometries. Alike EMM, WECM removes material electrochemically [1] where cathode wire and anode workpiece is submerged under desired electrolyte solution during machining and are separated by a suitable inter-electrode gap (IEG). Also, WECM can fabricate required microfeatures with desired geometries and with greater accuracy on different newly developed and difficult-to-cut materials such as stainless steel, titanium and titanium alloys, tungsten, nickel based metallic glass, nickel and cobalt based alloys, aluminum alloys [2], etc. Apart from other thermal induced material removal process like wire electro discharge machining (WEDM), WECM, as an environment friendly process, does not suffer from generation of thermal stress, formation of heat affected zone (HAZ), deterioration of surface quality as well as property, burr formation and tool wear [3]. Moreover, as the tool wear is not associated with WECM process, hence, very precise and accurate features can be fabricated using wire of smaller diameter. Also, wire feeding is not required in WECM which makes this process even much simple, stable and economical.

By using WECM, Zeng et al. [4] fabricated different micro structures such as micro grooves, micro spline, micro beam, micro gear, micro square helix etc. Zhu et al. [5] fabricated in situ wire electrode of 5 µm diameter and machined different complex micro structures. Wang et al. developed an overcut model for WECM and fabricated wafers form solar silicon ingot by using abrasive electrochemical method based on multi-wire saw system [6]. Qu et al. [7] introduced the combined method of vibrating anode with low frequency and travelling cathode in its axial direction to improve the homogeneity of micro features in WECM.

However, WECM is a newly developed process and it is still far from being familiar. Moreover, apart from other operating parameters, the performance of WECM process namely the dimensional features of fabricated products also depend upon the feed rate of cathode employed during machining. Too high feed rate will result in inappropriate flushing of machining products, namely sludge and gas bubbles, from the narrow machining zone that will lead to accumulation of machining products, sparking and short-circuiting in the IEG and in turn deteriorate the homogeneity and stability of the process. On the other hand, if the feed rate is too low, the effect of stray current will be much more prominent and the accuracy as well as dimensional characteristics of the generated micro feature will be degraded and distorted.

Hence, this research work is directed towards exploiting the capabilities and enlarging the boundaries of WECM process by step by step developing proper experimental setup for

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generating microfeatures. To enhance the flushing, proper electrolyte flow system has also been developed and introduced accordingly during machining. Also, after the experiments, the generated microslits have been carefully analyzed under optical microscope. Moreover, efforts have been made to investigate the effect of feed rate on the width of the fabricated microslits by determining suitable ranges of feed rate within which WECM process can result in stable, accurate and homogeneous machining.

2. EXPERIMENTAL SET UP

To carry out the experiments of WECM process on indigenously developed experimental set-up, various components of different sub-systems are procured as well as developed accordingly. Experimental setup for WECM consists of various sub-systems such as mechanical machining unit, power supply unit, electrolyte flow system etc. Mechanical machining unit consists of XYZ movement stage with position control unit, machining chamber, worktable and wire holding and tensioning block. The most important and sophisticated part of the mechanical machining system is XYZ movement stage with position control unit which moves the wire accurately and precisely with incremental steps of 0.3125µm in all the three directions of X, Y and Z. The mechanical machining unit holds the tool wire firmly in vertically tensed condition with the help of a wire holding and tensioning block which is mounted via an attachment on the Z-axis of the movement stage.

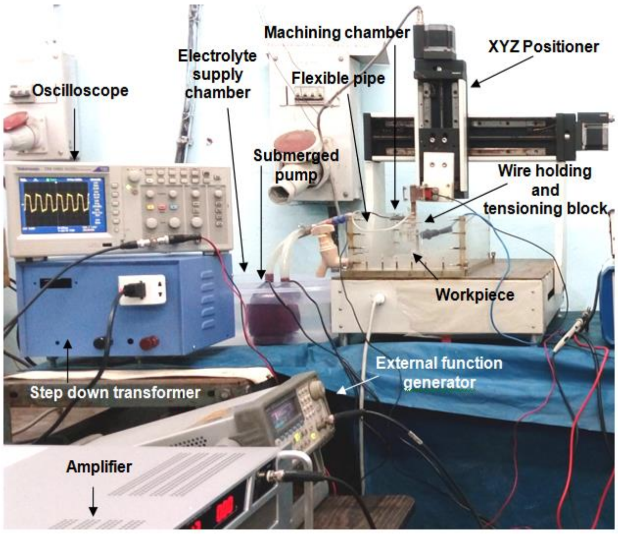

Fig.1.Photographic view of the developed experimental setup

The perspex made machining chamber holds the required electrolyte solution and has a special arrangement for workpiece clamping so that workpiece of different shapes and sizes can be fixed as well as undesired vibration due to the flow of the electrolyte can be prevented. Suitable axial electrolyte flow system consisting of submerged pump, electrolyte supply chamber, flexible pipe with micro nozzle, flow controller, flow positioner etc. has also been developed and utilized to supply the fresh electrolyte under constant flow rate and to carry out the machining products from the IEG. The D.C. power supply unit consists of an external function generator and amplifier. Furthermore, different other accessories like oscilloscope, multimeter, voltage stabilizer, step down transformer, stereo zoom microscope etc. have been utilized to carry out the experiments. A photographic view of the developed wire electrochemical machining setup has been shown in Fig. 1.

3. EXPERIMENTAL PLANNING

For carrying out required experiments, to define prime operating parameters and their values as well ranges, proper scheme has been designed utilizing the indigenously developed WECM setup. Here, based upon the developed setup and among diameters of wire starting from few micron, sets of experiments has been carried out by taking tungsten wire of diameter 50 µm as cathode whereas, stainless steel sheet (SS304) of 100 µm thickness has been taken as anode. Tungsten as a wire material has been selected in this study due to its higher tensile strength than commercially available platinum, molybdenum and copper wires. Dilute H_2SO_4 of concentration 0.1 M has been used during all experiments due to the fact that acid electrolyte produces less reaction products than normal salt electrolytes for which appropriate flushing of machining debris in the narrow IEG will occur during operations [8]. During experiments, as mentioned earlier, developed electrolyte flow system has been introduced for incorporating axial electrolyte flushing and to remove machining products from the IEG. Appropriate flushing of sludge and gas bubbles during machining results in minimizing the occurrence of sparking and short-circuits and leads to controlled machining as well as generation of homogeneous micro features. Based upon the developed experimental setup, the initial IEG has been set to 100 µm before the experiments. Depending upon the developed setup and experimental conditions, the operating parameters and their ranges have been decided after few trial experiments where applied voltage, duty ratio, frequency and concentration of electrolyte has been kept constant as 18V, 10%, 50 kHz and 0.1 M respectively and feed of wire electrode has been increased within the range of 1.875 micron/sec to 3.75 micron/sec with an incremental step 0.3125 micron. Application of voltage higher than 18V results in melting of tool wire whereas, below 10% duty ratio, machining does not occur. All the process parameter settings maintained during experiments has been listed in Table 1.

Table 1: Process parameters with their ranges

Parameters	Values and ranges
Applied voltage, V	18
Duty ratio, %	10
Applied frequency, kHz	50
Concentration of electrolyte (H_2SO_4), M	0.1
Feed rate of tool wire (µm/sec)	1.875-3.75

4. EXPERIMENTAL OBSERVATIONS AND DISCUSSIONS

After the experiments, the machined microslits have been carefully observed under optical microscope to verify the process feasibility as well as homogeneity of generated microslits and feasibility and to get more insight; the experimental observations have been discussed here. Fig. 2(a) shows optical micrograph of microslit fabricated with 18V, 10% duty ratio, 50 kHz frequency, 0.1 M H_2SO_4 and 1.875 micron/sec feed rate. Fig. 2(a) also reveals that the generated microslit is homogeneous as controlled dissolution is occurred. Moreover, no unevenness has been found due to the absence of any short circuit or sparking at this lower feed rate.

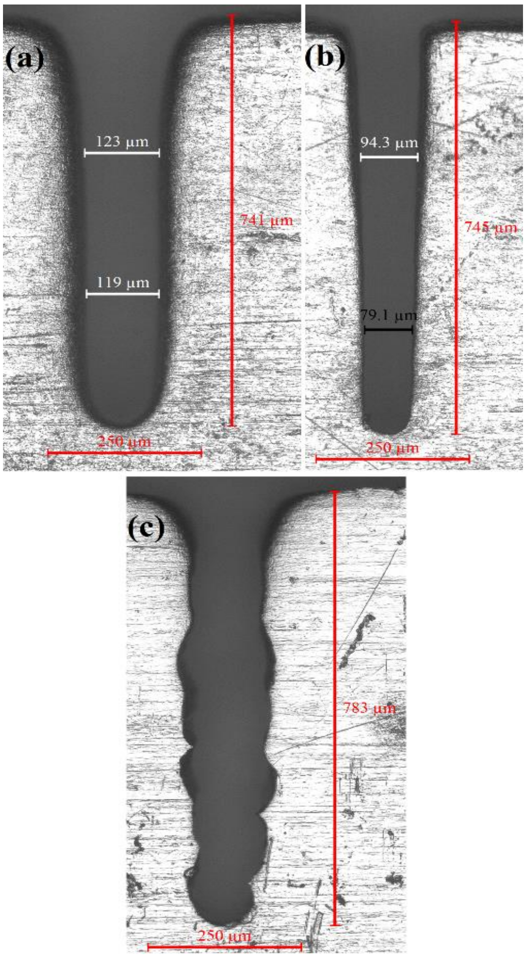

Fig.2.Optical images of the microslits fabricated with 18V, 10% duty ratio, 50 kHz frequency, 0.1 M H_2SO_4 and feed rate (a) 1.875 µm/sec, (b) 3.4375 µm/sec and (c) 4.0625 µm/sec.

Though at this lower feed rate few effects of stray current has been observed particularly in the sides of the microslit and entry point that resulted in increase in width at those portions. Moreover, the average width of the microslit is 121 µm which is a bit in higher side regarding the fact that tungsten wire of diameter as low as 50 µm has been used during experiments due to the application of such low feed rate. The length of the microslit is 741 µm and aspect ratio is 0.83. Fig. 2(b) shows optical micrograph of microslit fabricated with 18V, 10% duty ratio, 50 kHz frequency, 0.1 M H_2SO_4 and feed rate of 3.4375 micron/sec. Similarly, like Fig. 2(a), Fig. 2(b) shows homogenous microslit resulted from stable and controlled machining. Here, the overall effect of stray current is also lower due to application of higher feed rate, though some effect of stray current has been observed especially near entry point. Moreover, the average width of the microslit is lower i.e. 86.7 µm which means machining accuracy has also been increased due to the application of feed rate in higher ranges. The length of the microslit is 745 µm and aspect ratio is 1.15. Fig. 2(c) shows optical micrograph of microslit fabricated with 18V, 10% duty ratio, 50 kHz frequency, 0.1 M H_2SO_4 and feed rate as high as 4.0625 micron/sec. At this high feed rate which is beyond the experimental feed range, the widths of microslits starts to become so narrow that proper flushing and removal of electrolysis products from the tiny IEG becomes difficult. As a result of this uncontrolled and inhomogeneous machining, short-circuiting and sparking become prevalent which deteriorates the dimensional quality, decrease the accuracy and increases the average width of the microslit. The length of the microslit is 783 µm.

After obtaining the results from optical microscope, the average values of width of the fabricated microslits have been graphically represented to analyze the influence of corresponding WECM process parameter and keeping the other parameters constant, a graphical representation with varying values of feed rate has been plotted and discussed here under. Fig. 3 shows influence of feed rate on width of the fabricated microslit. The graph is plotted with the experimental results obtained with feed rate ranging from 1.875 micron/sec to 3.75 micron/sec, by keeping the other parameters as fixed as, 10% duty ratio; voltage, 18V; frequency, 50 kHz and concentration of electrolyte (H_2SO_4), 0.1 M. Here, the minimum average width of fabricated microslit achieved during experiments is 86.7 µm while the maximum average width is 116 µm. The graph reveals that the width of the microslit decreases with increasing feed rate upto 3.4375 µm/sec. Increase in feed rate means less machining time has been made available. As a result, the volume of material removal decreases and slit width also decreases. However, with increase in feed rate from 3.4375 µm/sec to 3.75 µm/sec the slit width increases slightly. This is due to uncontrolled and inhomogeneous machining resulting from short-circuiting, frequent sparking and accumulation of electrolysis products as the slit width is becoming narrower at this high feed values and flushing of sludge and gas bubbles is becoming inadequate.

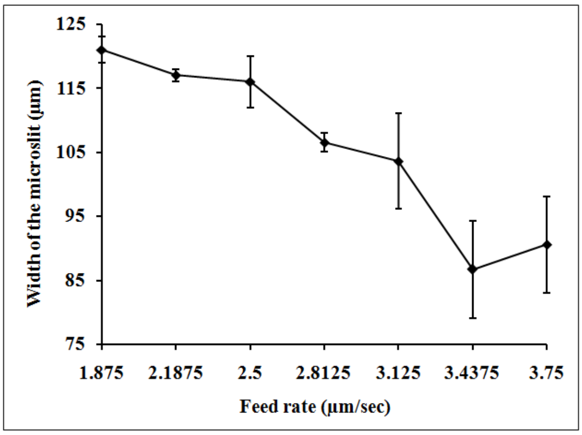

Fig.3.Influence of feed rate on width of the microslit

Moreover, the slope of the graph in the feed range of 3.125 µm/sec to 3.4375 µm/sec is steeper than the slope in the feed range of 1.875 µm/sec to 3.125 µm/sec. This is due to the reason that, at lower feed values, the dissolution is enhanced by effect of stray current which results in higher width of the microsilt. Whereas, at higher feed values the effect of stray current is minimum and most of the dissolution is constrained within the periphery of the tool wire. As a result, width of the microslits decreases rapidly.

5. FABRICATION OF COMPLEX MICROSLIT

After finding out the influence of feed rate on corresponding slit width, complex microfeature with varying cross-section has been fabricated by changing the feed values in order to justify the process feasibility and explore further capability. Fig. 4 shows a complex microslit of varying widths of 116 µm, 96 µm and 80 µm. The first portion which have a width of 116 µm is achieved by machining with 18V, 10% duty ratio, 50 kHz frequency, 0.1 M H_2SO_4 and feed rate of 2.5 micron/sec; the second portion with width of 96 µm is achieved by machining with 18V, 10% duty ratio, 50 kHz frequency, 0.1 M H_2SO_4 and feed rate of 3.125 micron/sec whereas, the third portion with the lowest width i.e. 80 µm has been machined with 18V, 10% duty ratio, 50 kHz frequency, 0.1 M H_2SO_4 and feed rate of 3.4375 micron/sec.

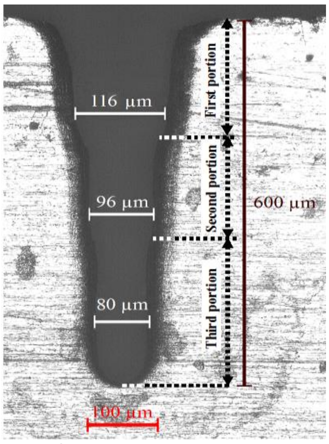

Fig.4. Fabrication of complex microslit by varying the feed rate

The machined complex microslit is quite smooth and homogeneous which is the result of controlled dissolution during machining. However, like previous, the slit width at entry point is higher and the effects of stray current particularly in the junction point of changing the feed values is predominant as feed rate is increased gradually from lower value to a higher value during machining. The larger overcut at the entry point is due to the high stray current effect resulting from application of high voltage associated with lower feed rate. Additionally, as the IEG is 100 µm, hence, with such low feed rate, it has taken a considerable amount of time to overcome the IEG making the effect of stray current more prominent and overcut larger. This taper formation can be minimized by making the dissolution more localized by careful selection of process parameter values, implementing better electrolyte flow system and reducing the initial IEG. However, the above observation also clearly identifies the fact that, micro features of different internal cross-sections can easily be fabricated by altering as well as controlling the corresponding process parameters which may have a great influence in ever growing fields like microfluidics.

6. CONCLUSIONS

The above experimental analysis highlights that parameters like feed rate of tool wire has a great influence on corresponding micromachining criteria and based on the above observations, following conclusions have been drawn

(i) Experiment with 18V, 10% duty ratio, 50 kHz frequency, 0.1 M H_2SO_4 as well as 1.875 µm/sec and 3.4375 µm /sec feed rate showed quite good, controlled homogeneous and stable machining where the microslits have been possible to fabricate with better accuracy. However, experiment with 18V, 10% duty ratio, 50 kHz frequency, 0.1 M H_2SO_4 and feed rate of 4.0625 µm/sec, which is beyond the selected range has showed uncontrolled and poor machining due to occurrence of frequent sparking and short-circuiting.

(ii) Experiment with increasing the feed values have resulted in generation of microslits with gradual decrease in the width. Moreover, the minimum average width of microslit achieved during experiments is 86.7 µm with an aspect ratio of 1.15, whereas, maximum average width is 116 µm.

(iii) Experiments with higher value of feed rate such as 3.75 µm/sec started showing abrupt change and increasing trend in width of the microslit due to coagulation of reaction products in the IEG due to uncontrolled machining.

(iv) Complex miroslit width varying cross-section has been fabricated by changing the corresponding feed values. Such type of microfeature may opt towards greater importance in the fields like microfluidics and other advanced engineering applications.

Fabrication of complex micro features has become a prime issue where WECM process can play a crucial role in machining desired micro products. However, in depth research is still needed to enhance further process capability and effectiveness by determining suitable machining conditions as well as strict control of operating parameters. Therefore, the future plan of this work will comprise of finding out the influence of other process parameters like applied voltage, duty ratio, frequency and concentration of electrolyte, which have been kept constant in this study and also their effects on corresponding feed values in order to achieve desired microfeatures with greater accuracy and lower machining time, applicable for batch scale production purposes.

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