International Journal of Engineering Research and Technology. ISSN 0974-3154 Volume 10, Number 1 (2017)

A Review and Case Study on Reverse micro-Electrical Discharge Machining Process

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Abstract
Reverse micro-Electrical Discharge Machining (R-µEDM) is one of the immerging technique in Electrical Discharge Machining (EDM) field. This process is used to fabricate high aspect ratio arrayed micro-features. These high aspect ratio arrayed micro-electrodes have wide application in EDM hole drilling of fuel injection nozzles, spinnerets, turbine blade, etc. With the help of these arrayed micro-features productivity can be improved. This paper highlights the work that has been carried out on R-µEDM process. The focus of discussion is on the understanding of the R-µEDM process, comparison of R-µEDM process with different micromachining process, effect of various process parameters on R-µEDM process and manufacturing of micro-pins. Fabricated micro-pins are having 500 µm diameter and 6.5 mm length. Gap voltage, Peak current and pulse on time are selected as process parameter while material removal rate is response parameter. Miro-pin fabricated are having high aspect ratio of 16.

Keywords: Reverse micro-EDM, Micro-electrode, Aspect ratio, Array micro-feature.

Introduction
EDM is among the earliest non-traditional manufacturing processes. In this process electrical energy is transformed into heat energy between the tool electrodes and the workpiece in fluidic medium, like EDM fluid or kerosene. This process is used to machine electrically conductive difficult-to-machine materials. Material gets eroded through repeated sparks struck between two electrodes. R-µEDM is variant of micro-EDM. Basic working principle of R-µEDM is same as that of EDM process but experimental procedure and applications are different [1].

In EDM drilling process, in order to create micro-holes we need electrodes. These electrodes can be manufactured by using micro-turning, micro-wire electrical discharge machining, micro-milling, LIGA and micro electrical discharge grinding process. But these processes have few limitations. Table 1 shows the various processes used in manufacturing of micro-electrodes, along with their capabilities and limitations. Hence in order to overcome these limitations reverse micro-Electrical Discharge machining process is developed. In R-µEDM process we can create array of electrodes at a time. These electrodes either can be of circular or polygonal shape. Time taken by this process is less and cost of the machining is also less.

R-µEDM is the process in which reverse replica of already drilled micro-cavities is produced on the workpiece. R-µEDM process is carried out in two steps. In first step cavities are created on the plate electrode with the help of micro-machining process. In second step, plate electrode is mounted on the micro-EDM machine in order to produce reverse replica of those cavities on workpiece.

Figure 1 shows the schematic setup of the R-µEDM process. The plate electrode is having negative charge whereas workpiece is having positive charge. When electrons transferred from negative charge to positive charge, it creates large amount of heat energy. Because of this energy, small amount of material gets removed from workpiece resulting in formation of crater on workpiece surface and machining is carried out [2]. Electrodes fabricated through this process are having wide applications in biomedical engineering, aerospace, automobile, heat exchangers and micro-EDM drilling.

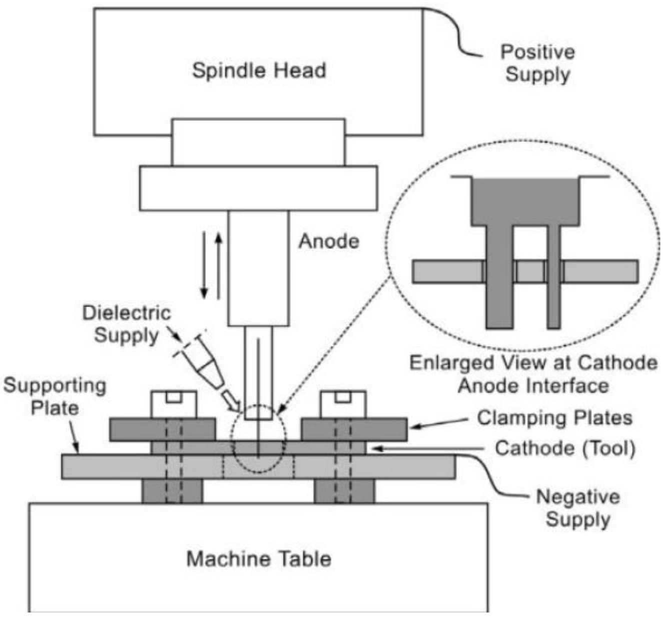
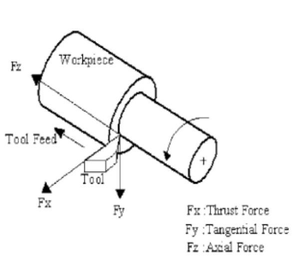
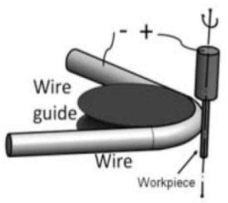
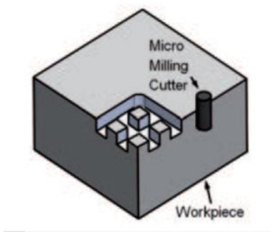
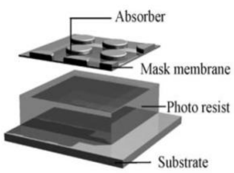


Figure 1: Schematic setup of the R-µEDM process [2]

Table 1: Summary of processes used in fabrication of micro-electrodes [3-7]

Reference	Process	Schematic of Setup	Capability	Limitation
Rahman et al. [3]	Micro-Turning	 	276 µm diameter of pin with 2 mm length	At a time single electrode can be fabricated
Chen [4]	Micro-WEDM	 	Minimum machining size achievable is 20 µm, 10 * 10 square rods	Only polygonal shape micro-electrodes can be fabricated
Liu at al. [5]	Micro-WEDG	 	Pin having 5 µm diameter and 50 µm length can be fabricated	Only single electrode of circular cross section can be fabricated
Takeuchi et al. [6]	Micro-Milling	 	Square micropins of 25 µm and height 1000 µm	Interspacing between two micropins is large
Tseng et al. [7]	LIGA	 	100 µm diameter micropin	Expensive process

Literature Review

Reverse micro-Electrical Discharge machining process has been started by Kim et al. [8] in 2004. Later on few other researchers also started to do research in this field. Process parameters play a key role in the performance of the R-µEDM process. In order to understand the effect of various process parameters and technological advancement in reverse micro-electrical discharge machining process, there is necessity to carry out literature survey of this process. Table 2 shows Technological advancement in reverse micro-Electrical Discharge machining process.

Table 2: Technological advancement in Reverse micro-Electrical Discharge machining [8-15]

Reference	Workpiece, plate material, Dielectric fluid	Process parameters	Research Finding
Kim et al. [8]	Tungsten carbide, Copper, EDM oil	Voltage- 80, 100 V Capacitance- 50, 650, 5000 pF Feed rate- 1μm/s	Energy is directly proportional to capacitance and square of voltage. Hence with increase in voltage and capacitance value discharge energy increases and large amount of material is removed from workpiece. Multiple electrodes formed through R-μEDM were further used in micro-ECM process.
Lee et al. [9]	Tungsten Copper, Copper, EDM oil	Current- 12 to 64 A, Voltage - 80 to 200 V	They have analyzed the effect of positive and negative polarity on MRR. At negative polarity the material removal rate is higher and at the same time relative wear ratio is lower. Negative polarity is suitable for both high peak and low peak current operations. Good material removal rate is achieved in finish machining with negative polarity.
Mujumdar et al. [10]	Brass, Copper, De-ionized water	Voltage - 80, 100 V Capacitance - 1, 10 nF Feed rate - 5,15 μm/s	They have studied the dimensional accuracy of the micropins at the root and tip of the micropin. The absolute value of percentage error in the diameter of the micropin decreases at the tip and it increases at the root. The reason behind this was secondary sparking. Hence proper flushing of the debris material was needed.
Singh et al. [11]	Tungsten, Copper, Hydrocarbon oil	Capacitance - 100, 1000 pF, Voltage - 80, 100, 120, 140 V, Feed rate- 5, 10, 20 μm/s	They have found out that deviation in the average diameter can be minimized with the decrease in gap voltage. At low gap voltage small amount of energy was supplied at the machining zone hence amount of material removed was less. But at the same time, machining time increases hence optimum value of gap voltage must be selected.
Mastud et al. [12]	Tungsten carbide, Tungsten copper, EDM oil	Voltage- 80, 100, 120 V, Capacitance – 10, 100 nF, Feed rate- 5, 13, 25 μm/s	They have observed that, rough and pitted surface was at the tip of micro-rods, whereas at root it was smooth and uniform. Due to the secondary sparking at the tip of the micro-pin, surface becomes rough. With increase in capacitance value, secondary arcing tendency also increases.
Hawang et al. [13]	Tungsten carbide, Brass	Voltage - 90 V Pulse on time - 1 μs Capacitance - 0.01 μF Pulse off time - 20 μs	In order to reduce the debris accumulation in machining zone, they have provided vibrations to the electrode. This results in a huge gap between the workpiece and the electrode and at the same time working fluid continuously spraying upward from the bottom of the electrode. This results in to pumping effect which removes debris easily. It was also observed that there was reduction of the length of the micro-pin from outer laps to the inner laps and it was because of the debris accumulation in the inner lap which causes secondary sparking, hence length of the micro-pin get reduced.
Mastud et al. [14]	Ti6Al4V alloy, Copper, EDM oil	Voltage - 100, 130 V Capacitance - 1, 10 nF Amplitude - 0.5, 2 μm Freq.- 3, 6 KHz	They have observed that the micro pillars were taper in shape. It is because of the uneven distribution of the electric field intensity and secondary discharges due to accumulation of the debris in the electrode gap. Hence vibrations are provided to electrode for easy debris flushing.
Kumar and Agrawal [15]	AISI 1045, Copper	Current - 2, 4, 6, Pulse Duration -100, 200, 300 μs, Duty factor - 0.5,0.7,0.9	They have studied the effect of current and pulse duration on the surface roughness. At high current with short pulse duration the surface roughness is more whereas, at high current and long pulse duration surface finish is good.

From the literature review it is observed that, gap voltage, capacitance, feed rate, pulse on time and pulse off time decides the response parameters like Material Removal rate (MRR), surface roughness and workpiece accuracy. Material removal rate is mostly affected by voltage and capacitance, whereas surface roughness is by pulse on time. In R-μEDM debris removal from the machining zone is one of the main problem. Debris entrapment in the holes disturbs dimensional accuracy of the micro-pin. Hence it is noted that there is need to provide an extra arrangement for better flushing of the debris using dielectric fluid.

Experimental Study

The experimental study is carried out in order to find out the machining characteristics of R-μEDM process on brass material. Normal R-μEDM process is used in experimentation in which plate electrode is fixed on the machine table and workpiece is fed on to plate electrode. In this case plate electrode is act as cathode and workpiece is act as an anode. Experimentation was carried out in two steps. In first step, array of four holes each of 500 μm diameter were drilled on plate electrode (copper material 2.5 mm thick) with conventional micro-drilling process. Then that plate electrode is clamped on the machine table of CNC-EDM machine. In second step, bulk workpiece rod (brass material 4 mm diameter) is fed on to the plate electrode and micropins are manufactured. Figure 2(a) and 2(b) shows the photograph of actual setup for micro-drilling process on Micromachining center and photograph of actual setup of R-μEDM on CNC-EDM respectively. Taguchi method is used to design the experiments. From the literature review, gap voltage, peak current and pulse on time are selected as process parameters. Experiments are performed with L9 orthogonal array. Table 3 shows experimental conditions along with process parameters and their levels.

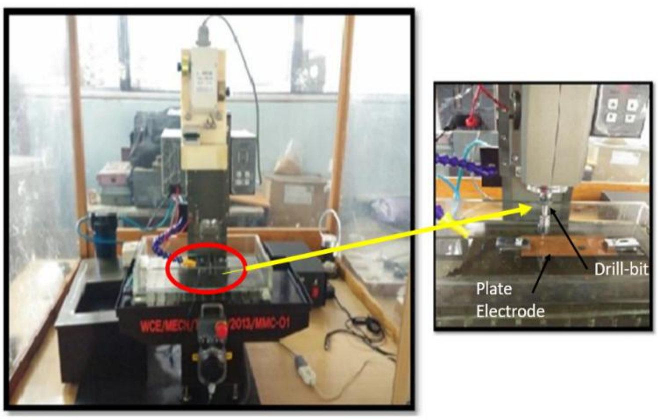


Figure 2 (a): Photograph of actual setup for micro-drilling process

Figure 2 (b): Photograph of actual setup of R-μEDM process.

Table 3: Experimental conditions

	Electrodes		Polarity
Workpiece material	Brass		Anode
Plate material	Copper		Cathode
Geometry	500 μm diameter micro-pin		
Dielectric	EDM oil		
Electrode position	Normal EDM		
Process parameters and levels			
Parameters	Level 1	Level 2	Level 3
Peak current (A)	2	3	4
Gap Voltage (V)	60	90	120
Pulse on time (μs)	100	200	300

Results and Discussions

In this work, evaluation of the R-μEDM process can be carried out on the basis of material removal rate. For optimum performance of the R-μEDM process, larger the better signal-to-noise ratio is used for material removal rate. Figure 3 and 4 shows the actual photograph of array of holes after machining and array of micro-pins, taken by optical camera. Table 4 shows F and P values of analysis of variance for material removal rate with respect to peak current, gap voltage and pulse on time.

Figure 3: Photograph of array of holes after machining

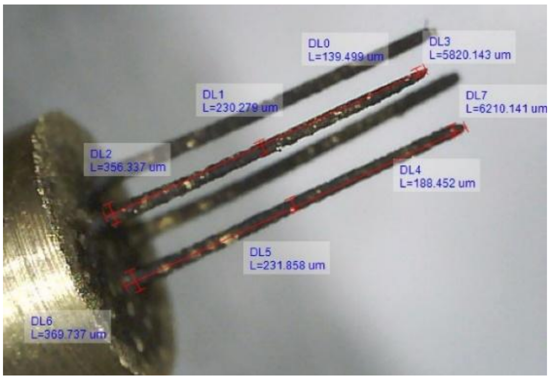


Figure 4: Photograph of fabricated micro-pins

Table 4: F and P values of ANOVA for MRR

		Material removal rate	
Source	DF	F-Value	P-Value
Peak Current (A)	2	36.25	**0.027**
Gap Voltage (V)	2	11.55	**0.080**
Pulse On Time (μs)	2	1.31	0.433
Error	2		
Total	8		
R-Sq = 98.00%R-Sq (adj) = 92.02%			

Analysis of material removal rate (MRR)
Material removal rate is amount of material removed per unit time. Main effect plot for material removal rate is shown in figure 5. From the main effect plot of MRR we can see that, MRR increases with increase in peak current value. The increase in spark discharge energy facilitates the action of melting and vaporization of workpiece material. Also it helps in advancing the large impulsive force in the spark gap which improves the MRR. It is also observed that with increase in gap voltage MRR decreases. The reason behind this is that, with increase in gap voltage, gap distance for initiation of a discharge increases. Hence spark travel distance increases, due to which intensity of spark is decreases and less amount of energy is supplied at machining zone. Hence less amount of material removed [16, 17].

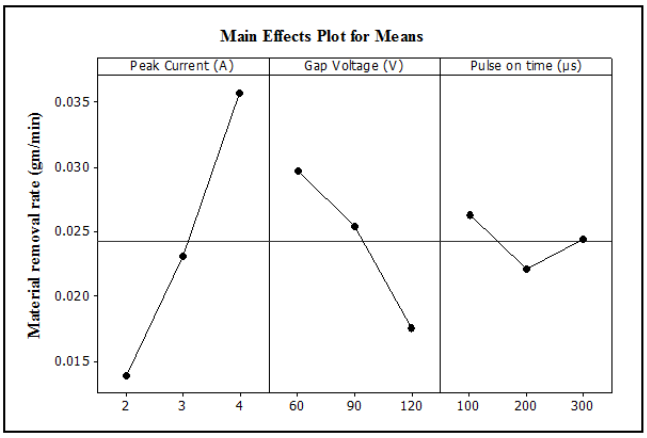


Figure 5: Main effect plot for MRR

Conclusions
In this study, effect of machining parameters such as Peak current (A), Gap voltage (V) and Pulse on time (μsec) on the response variables Material removal rate (gm/min) is investigated experimentally in R-μEDM process.
Based on study following conclusions are drawn.

- Peak current and gap voltage are the two factors that influence the material removal rate more. With increase in the gap voltage, MRR decreases. This shows reverse trend when compared with normal EDM process.
- From literature review it is clear that, surface roughness is more dominantly affected by peak current and pulse duration.
- It is observed that, fabricated pins are having uneven length. It is mainly because of the secondary sparking occurring because of the debris entrapment in the machining zone. Hence there is need to provide an extra arrangement for better flushing of debris material using dielectric fluid.
- It is also found that, pin accuracy is depend on amount of energy supplied per unit time. At high energy per unit time, pins are having more deviation from their required dimensions.
- Micro-pin of 500 μm diameter and the length of 6 mm is fabricated by R-μEDM process. Highest aspect ratio of the micro-pin achieved is 16.

Acknowledgement
The authors are thankful to AICTE-India for providing financial support under Research Promotion Scheme (RPS) to perform research in EDM process.

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