Analysis of Influence of micro-EDM Parameters on MRR, TWR and Ra in Machining Ni-Ti Shape Memory Alloy

Mohammed Sarvar Rasheed, A. M. Al-Ahmari, A. M. El-Tamimi, Mustufa H. Abidi

Abstract— In the micro-machining and MEMS industry, micro-Electrical discharge machining (μ-EDM) is an important process. In this paper, the Taguchi design approach has been employed to investigate the micro-EDM parameters in order to achieve the highest Material Removal Rate (MRR), good surface quality and low Tool Wear Rate (TWR) while machining Ni-Ti based Shape Memory Alloy (SMA). Based on these investigations, it has been observed that MRR is highly influenced by capacitance, discharge voltage and depends upon electrode material. TWR and Ra were found to be better at low energy levels. Tungsten electrode is recommended for better surface roughness and brass electrode for better MRR. SEM images have been used to observe the dimensional accuracy of micro-holes produced.

Index Terms—micro-EDM, micro-holes, Ni-Ti Shape Memory Alloy.

I. INTRODUCTION

Rapid developments in the micro-machining and use of advanced engineering materials have resulted in the increased demand for micro-structures in various industries such as aerospace, the communication industry and MEMS. Ni-Ti is considered as a most promising and widely used SMA in various fields and applications such as aerospace, bio-medical applications, MEMS, sensors, actuators and coupling etc [1]. In bio-medical applications, Ni-Ti SMA is used in cardio-vascular systems for minimal invasive surgeries [2]. Shape Memory Alloy (SMA) is an advanced engineering material which exhibits shape memory effects and other properties. The high strength, high wear resistance, pseudo plasticity and outstanding biocompatibility make the machining of Ni-Ti SMA complicated using conventional methods [3]. Therefore, machining of Ni-Ti SMA requires non-conventional machining processes such as EDM and laser machining [4].

Micro-holes are produced by different machining techniques but among all the machining processes, micro-EDM is considered as the best process for producing micro-holes because of its many advantages such as low apparatus cost, high aspect ratio and capability to fabricate hard-to-cut materials. Micro-EDM has similar characteristics as that of EDM except a difference in the size of the tool, discharge energy and axes movements which are generally in micron-levels [5]. Micro-EDM is a spark erosion process in which machining is performed by a sequence of electrical discharge generated by an electric pulse generator at short intervals between tool electrode and workpiece (conductive materials). During the electrical discharge, evaporation and melting of the workpiece takes place [6]. Micro-EDM is the main process for producing diesel and gasoline injection nozzles generally with a hole diameter less than 200μm [7]. Micro-EDM is also used for producing micro-holes in a turbine blade for cooling effect in aeronautics applications [8]. Ink jet nozzles are fabricated with micro-EDM [9] and it's reported that the first micro-holes for ink-jet nozzles of a printer were drilled on EDM by Sato et al. [10].

In any kind of machining whether it's conventional or non-conventional, adequate selection of machining parameters is most important. Jahan et al. investigated the influence of main parameters on the performance of micro-EDM with WC electrodes while producing quality micro-holes in both transistor- and RC-type generators [11]. Son et al. investigated the influence of EDM parameters especially pulse duration, on micro-EDM characteristics such as material removal rate and machining accuracy [12]. Yan et al. described the characteristics of micro-hole of carbide produced by micro-EDM using copper tool electrode and investigated the effects various machining parameters on the quality of micro-holes [13]. M.P. Jahan et al. studied the quality of micro holes produced by micro-EDM and investigated the influence of parameters on the performance of micro-EDM of WC in obtaining high quality micro-holes, good surface finish and circularity [14]. Pradhan studied the optimization of micro-EDM parameters for machining Ti-6Al-4V super alloy by using Taguchi Method for the responses MRR, TWR, overcut (OC) and taper. The optimal combination levels were obtained using ANOVA and S/N ratio graphs [15].

In this research work, an attempt has been made to study the effects of parameters which influence the micro electro-discharge machining of Ni-Ti alloy on the responses such as MRR, TWR and Surface Roughness (Ra). Analysis based on ANOVA and the Taguchi method has been carried out in determining the significant process parameters and their optimal combination levels for effective micro-holes generation. Based on these factors, a mathematical model which shows the relationship among responses and various independent variables of micro-EDM has been developed.

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A further study has also been carried out for studying the surface topography of micro-holes produced using SEM micrographs.

II. EXPERIMENTAL PROCEDURE

A. Machining Set-up

The experimental set-up shown in the fig.1 has been used to study the micro-EDM process. This set up can be used for both machining and investigating the micro-holes through microscope lenses without removing the workpiece from the worktable. The present experimental set-up used to study the micro-EDM process consists of a RC type generator. This generator can produce pulses from few tens of nano-seconds to few micro-seconds. The power supply can vary voltage levels from 45V to 120 V. An Optical microscope is used to investigate the micro-holes formed by micro-EDM set up. Fig. 2 shows a schematic diagram of μ-EDM.

Fig.1. Micro-EDM Set-Up (T.Masuzawa)

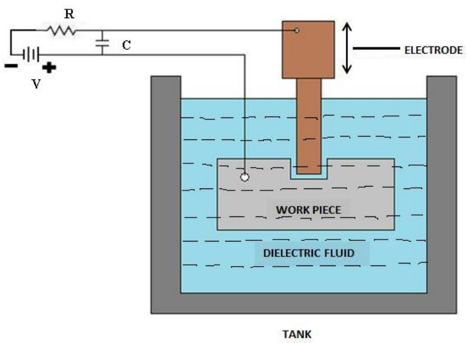

Fig.2. Schematic diagram of Micro-EDM

B. Workpiece and Electrode Materials

The workpiece material used for investigation consisted of Ni-Ti based Shape Memory Alloys as shown in the Table I. The electrode (tool) materials used were tungsten and brass cylindrical rod with a diameter of 100μm. Though, there are many commercially available dielectric fluids, kerosene was used as a dielectric fluid.

Table1: Workpiece material properties

Workpiece Material	**Ni-Ti (Shape Memory Alloy)**
Composition	Ni: 55.8%, Ti: 44.2%, C<0.02%
Density (kg/m3)	6500
Melting Point (°C)	1310
Electrical Resistivity (μΩ-m)	820
Modulus of Elasticity (Mpa)	41-75 x10 3
Total Elongation (%)	10

C. Design of Experiments (DOE)

The design of experiment is a statistical technique and powerful analyzing tool that is used to analyze the effect of more than one factor on the different responses at the same time. In this study, the Taguchi method is implemented by customizing the full factorial design to determine the effect of machining parameters on the micro-EDM process. In DOE, Taguchi method is very useful in process optimization and for finding the optimal combination of parameters which affects the given responses. The Signal to Noise (S/N) ratio calculates the variation present in the process and is used to measure the effect of noise factor on the performance characteristics. The S/N ratios are of three types: "smaller the better", "nominal the better" and "larger the better". The Analysis of Variance (ANOVA) is used to find out significant effects of each factor and their interactions on process responses [16].

$$\eta=-10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2}\right] \text{ ----------------- (1)}$$

$$\eta=-10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}{y_i}^2\right] \text{ --------------- (2)}$$

Equation (1) represents for "larger the better" and equation (2) is "smaller the better".

Where, 'η' is the S/N ratio and 'Y_i' is the experimental observed value and 'n' is the number of repeatations of each experiment.

In the present investigation, 24 experiments were carried out based on a full factorial model and the design matrix shown in the table 2 was customized according to the Taguchi methodology. The experimental data was analyzed using MINTAB 16 software dedicated for DOE. For measuring the quality of the performance characteristics, the experimental data was transformed into S/N ratios. The input parameters considered in this study were capacitance, discharge voltage and electrode materials and the responses included were Material removal rate (MRR), Tool wear rate (TWR) and the Surface roughness (Ra).

Table 2: Design matrix of experiments and responses

Exp.no	Capacitance (pF)	Discharge Voltage (V)	Electrode Material	MRR(mm3/min)	Ra (um)	TWR (mm3/min)
1	155	80	Brass	0.000263722	0.1028	0.00014241
2	475	80	Brass	0.000585787	0.128	0.000240173
3	155	100	Brass	0.000369049	0.1218	4.42859E-05
4	475	100	Brass	0.000953832	0.1432	0.000136398
5	155	80	Tungsten	0.000168331	0.09701	5.04993E-05
6	475	80	Tungsten	0.000398335	0.1108	0.000163317
7	155	100	Tungsten	0.000194472	0.1092	6.02863E-05
8	475	100	Tungsten	0.000510249	0.1252	0.000214305
9	155	80	Brass	0.00033818	0.0912	0.00013933
10	475	80	Brass	0.0005892	0.1139	0.000212112
11	155	100	Brass	0.00035225	0.10121	0.00021135
12	475	100	Brass	0.00112196	0.1281	0.000729274
13	155	80	Tungsten	0.00016083	0.079	4.50324E-05
14	475	80	Tungsten	0.000452616	0.1041	0.000153889
15	155	100	Tungsten	0.000189217	0.0891	6.07387E-05
16	475	100	Tungsten	0.00051809	0.1021	0.000202055
17	155	80	Brass	0.000350149	0.0982	0.000175075
18	475	80	Brass	0.000586367	0.1081	0.000229856
19	155	100	Brass	0.00037313	0.09912	0.000208953
20	475	100	Brass	0.00126105	0.13341	0.000781851
21	155	80	Tungsten	0.000149003	0.0829	4.64889E-05
22	475	80	Tungsten	0.000453917	0.0972	0.000195184
23	155	100	Tungsten	0.00018772	0.0912	7.88424E-05
24	475	100	Tungsten	0.000507698	0.11812	0.000284311

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MRR is an important response because it largely determines the efficiency and cost effectiveness of the process. The MRR is calculated as the average of the material removed to the machining time and generally expressed in cubic millimeters per minute. The general Volume formula considered for MRR in a workpiece was Volume of a conical frustum and cylindrical volume over the machining time was adopted for TWR to make a through hole as given below.

Material Removal Rate (MRR) = $\{\prod/3\ [R^2_t + R_t R_b + R^2_b]\ x\ p\} \div t$

Where, ' R_t' and 'R_b' are the radius at the entrance and bottom of the micro-hole.

'p' is the thickness of work piece material and 't' is the machining time to make a micro-hole.

Tool Wear Rate (TWR) = $\{(\prod\ D^2\ q)/4t\}$
Where 'D' is the tool diameter, 'q' is the frontal electrode wear and't' is the time to machine a through hole.

Scanning Electron Microscope(SEM) micrographs were used to measure after machining. The reduction in electrode length due to wear was measured by capturing images of the electrodes before and after the machining. The Surface roughness (Ra) on the holes side walls were measured using Talysurf CCI 600 instrumets.

III. RESULTS AND DISCUSSIONS

A. *Effect of EDM Parameters on Responses using S/N ratio Analysis*

In this experimental study, the main objective was to find out the significant factors that influenced the electric discharge machining of Ni-Ti SMA. The S/N ratios were used to analyze the responses for a given set of input parameters. The ranking of the main parameters (capacitance, discharge voltage, electrode material) affecting the MRR, TWR, Ra using S/N ratios was obtained as shown in the table 3, 4, 5. From these tables, it can be concluded that the factor that largely influenced the output responses was capacitance. The electrode material and discharge voltage were also found to be significant factors influencing the responses. Fig. 3, fig. 4, fig.5 represents the main effects S/N ratio plot for MRR, TWR and Ra and the experimental results obtained using S/N ratio graphs suggests that the optimal condition for maximum MRR was at Capacitance = 475 pF, Discharge voltage = 100V and brass electrode and the conditions that resulted in minimum TWR were capacitance = 155 pF, Discharge Voltage = 80V and with tungsten electrode. Similarly, the Surface roughness (Ra) for better surface was found at the following optimal conditions capacitance = 155 pF, Discharge Voltage = 80 V and Tungsten electrode material.

Table 3: MRR-Response table for S/N ratio

Levels	Capacitance (pF)	Discharge Voltage (V)	Electrode Material
1	-72.33	-69.52	-65.71
2	-64.24	-67.06	-70.87
Delta	8.09	2.46	5.12
Rank	1	3	2

Table 4: TWR-Response table for S/N ratio

Levels	Capacitance (pF)	Discharge Voltage (V)	Electrode Material
1	80.36	77.74	72.12
2	71.20	73.83	79.44
Delta	9.16	3.91	7.32
Rank	1	3	2

Table 5: Ra-Response table for S/N ratio

Levels	Capacitance (pF)	Discharge Voltage (V)	Electrode Material
1	20.27	19.94	18.90
2	18.60	18.94	19.98
Delta	1.66	1.00	1.08
Rank	1	3	2

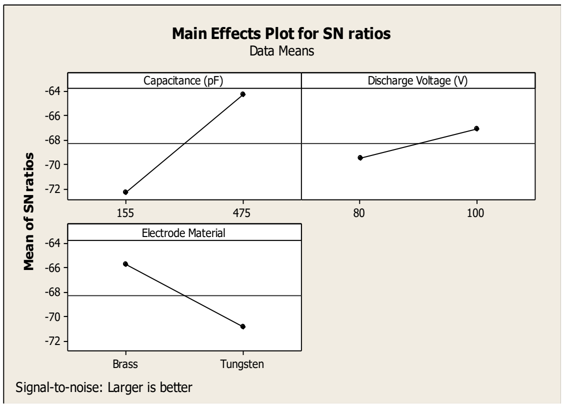

Fig.3. MRR main effect S/N ratio plot

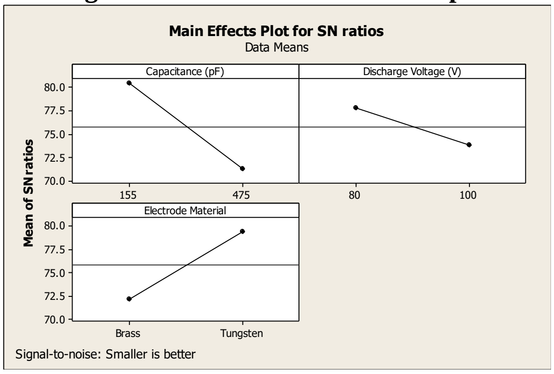

Fig.4. TWR main effect S/N ratio plot

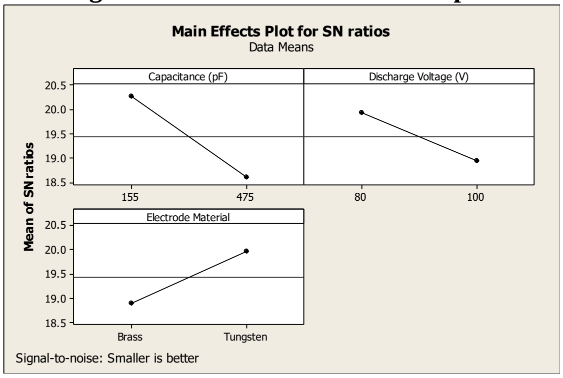

Fig.4. Ra main effect S/N ratio plot

B. *Effect of input parameters on MRR*

In any kind of machining process, MRR is considered to be an important machining characteristic. Micro-EDM is an electric thermal process, in which the energy supplied by the generator is converted into thermal

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energy which results in a rise in temperature of workpiece and electrode material to remove material by means of melting and evaporation. In RC type of generators, the capacitor stores the energy and this energy is discharged during the machining process. Besides discharging energy the electrical and thermal properties of workpiece and electrode materials also plays an important role in the material removal process. From the main effect plot for MRR shown in the fig.6, it was observed that MRR increases linearly with the increase in energy levels (capacitor) and it was also observed that MRR increases with the increase in discharge voltage.

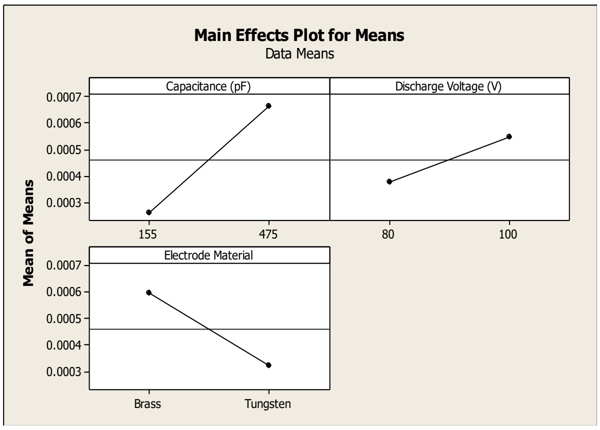

Fig.6. MRR-Main effect plot for means

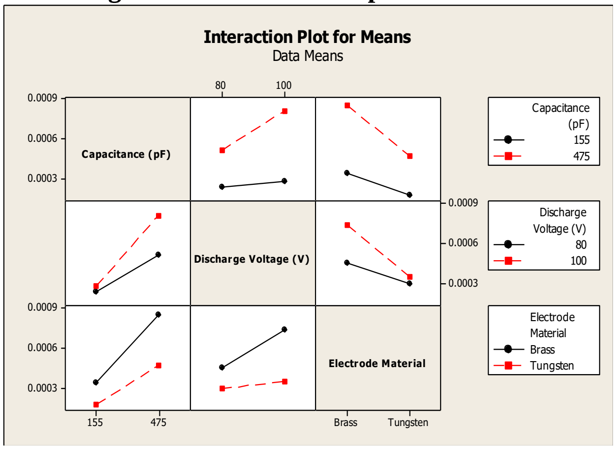

Fig.7. MRR-Interaction plot for means

The increase in discharge energy leads to strong sparks, which heats up the workpiece material to a very high temperature and enhances the erosion process, resulting in higher MRR. Sometimes, variation in discharge energy leads to variations in MRR. These variations may be due to non-uniform distribution of discharge energy during machining generated by RC generator at low energy levels [17]. The other reason for lower MRR can be small working gap i.e., the distance between the tool electrode and workpiece during machining as a result of low discharge voltage. The improper dielectric flushing in the working gap might lead to short circuiting and arching, thus reducing the MRR. From Fig.7, it is observed that all main effects and their interactions influence the MRR, but capacitance Vs discharge voltage interaction has the largest influence followed by discharge voltage Vs electrode material and capacitance Vs electrode material. In addition to the input parameters, the thermal and electrical properties of the electrode and workpiece materials have a significant effect on MRR. It was found that MRR is better using brass electrode compared to tungsten electrode material.

C. Effect of input parameters on TWR

In micro-EDM, Tool wear rate (TWR) also plays an important role for determining the dimensional inaccuray of the micro-hole produced. It was obsereved that with an increase in discharge energy, TWR also increases [18]. From the fig. 9 representing TWR main effect plot for means, it can be concluded that TWR increases with an increase in capacitance and also increases with an increase in discharge voltage for both tungsten and brass electrodes material.

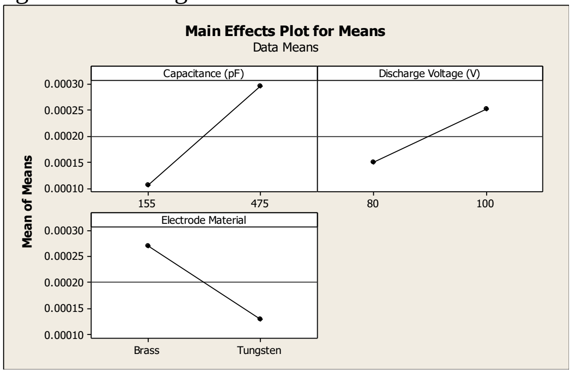

Fig.8. TWR-Main effect plot for means

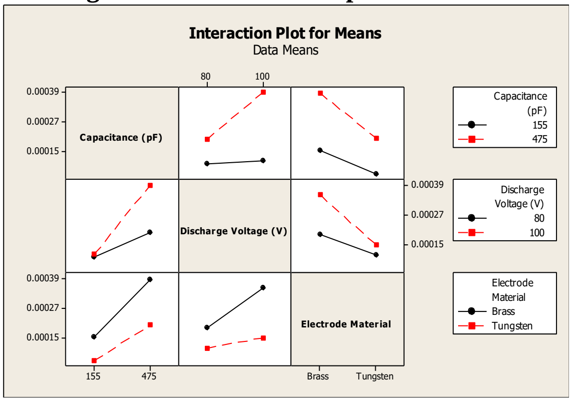

Fig.7. TWR-Interaction plot for means

TWR rises with an increase in discharge energy due to access in craters size, which is formed at the machining surface as a result of more removal of material from both workpiece and the electrode material.

The debris in the gap increase short circuiting and arcing and improper flushing leads to an increase in TWR. In addition to the discharge energy, workpiece and electrode material, aspect ratio, electrical and thermal properties of the materials also plays an important role in TWR during micro-EDM process [19]. Although, it was observed that the TWR in brass electrode is higher than the tungsten electrode material. This may be due to the higher melting and boiling point of tungsten material which possess high thermal capabality with excellent wear resistnace [20]. The type of dielectric fluid used also has significant effect on TWR. When kerosene is used as a dielectric fluid in EDM process a carbide layer is formed on the workpiece material which needs higher energy for melting and evaporation as a result Tool wear [21]. From the interaction plot for TWR shown in the fig.9, it can be concluded that TWR is mostly influenced by capaciatnce and discharge voltage interaction, followed by the interaction of discharge voltage and electrode material.

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D. Effect of input parameters on Ra

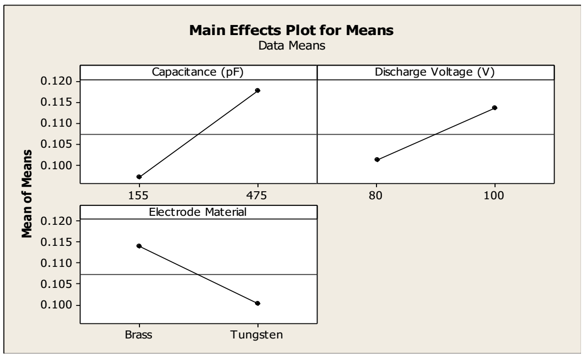

Fig.10. Ra-Main effect plot for means

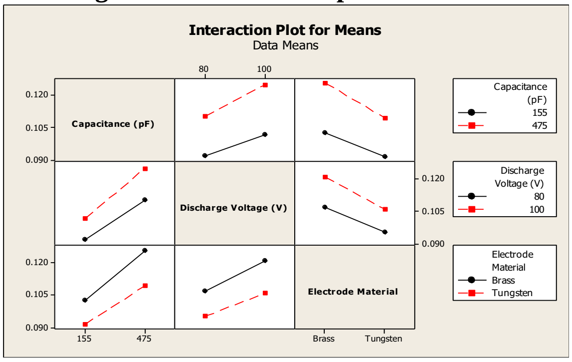

Fig.10. Ra-Interaction plot for means

From the main effect plot for surface roughness (Ra) shown in the fig.10, it can be concluded that with an increase in the capacitance and discharge voltage, discharge energy increases thus increasing the surface roughness. The increase in discharge energy increases the sparks intensity which helps in melting and vaporization of the workpiece and electrode material. As a result, the crater size increases on the surface of the workpiece material thus resulted in increased surface roughness. It was also observed that the surface roughness (Ra) with brass electrode is more than compared to that of tungsten material. From the interaction plot shown in the fig. 11, it can be concluded that there are no significant effects of interaction on surface roughness. It is recommended that for better surface finish, low capacitance and discharge voltage can be used. In micro-holes, surface quality is mainly considered based on crater size; and micro-holes with smaller and uniform distribution of crater have a good quality surface finish. From the experimental investigations, the smaller crater sizes have been observed at small discharge energy levels with less material removal per pulse. By setting the RC-type pulse generator at small discharge energy level with low capacitance and at lower voltage, a better surface quality can be obtained. Fig.12.a and fig. 12.b shows the SEM images of micro-holes produced using brass and tungsten electrode.

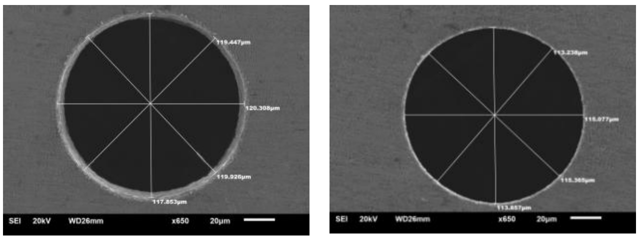

Fig. 12 (a) Holes shapes at entrance (left) and exit (right), using 100 µm diameter brass electrodes.

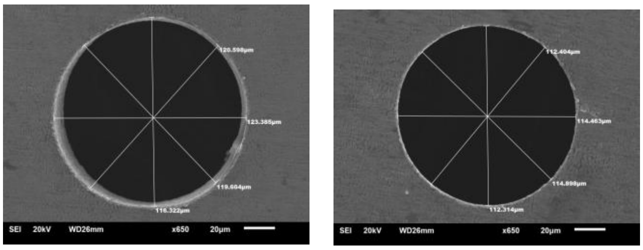

Fig. 12 (b) Holes shapes at entrance (left) and exit (right), using 100 µm diameter tungsten electrodes.

IV. CONCLUSION

The present investigation is effective in achieving the desired out come from the design of experiments. Taguchi design of experiment has found to be successful in analyzing the optimum condition of parameters which influence the responses such as MRR, TWR and Ra. From the experimental result analysis using S/N ratio, main effect and the significance of individual parameters and their interactions to MRR, TWR and Ra, it has been found that the capacitance is the most influencing factor on MRR, TWR and Ra. It can also be concluded that MRR increases with an increase in capacitance and discharge voltage for both tungsten and brass electrode, but it significantly affects the surface quality of micro-holes due to increase in crater size on the drilled surface. It has also been observed that electrical and thermal properties of electrode and workpiece material significantly affect the responses. TWR in tungsten electrode has found to be less compared to brass electrode. Finally, it can be concluded that while machining Ni-Ti SMA, a brass electrode should be used if MRR is an important requirement. For better surface roughness and dimensional accuracy of micro-holes, tungsten electrode is preferred.

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