Taperness and Linear Wear Rate Analysis of High Aspect Ratio EDM Meso-Holes in Ti-6Al-4V

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Abstract. EDM using rotary tube electrode is best suited for machining high aspect ratio meso-holes in Ti-6Al-4V. In this paperwork, we have analyzed taperness and linear wear rate of the electrode for implementation of high aspect ratio EDM in drilling meso-holes. An experimental layout is prepared to use Taguchi's L 27 orthogonal array. The 300 µm brass tube electrode was selected with high accuracy for the entire experiment. Using TOPSIS the optimized input parameters (current, gap voltage, on-time, and off-time) are selected for responses such as taperness and linear wear rate among the available. By the measurement minimum, taperness of 0.0029^o and linear wear rate of 1.5131 mm/sec were observed in EDM using brass tube electrodes.

1. Introduction

Ti-6Al-4V is one of the hard, tough and strong material possesses the high melting temperature and corrosion resistance because of its find wide applications in biomedical, aerospace, marine, power generation and offshore industries [1-3]. The conventional machining of Ti-6Al-4V yields very poorer manufacturing attributes such as time, quality, and money and flexibility. All these manufacturing difficulties are eliminated by Electric Discharge Machining (EDM) [4]. But machining high aspect ratio is difficult in EDM [5]. A rotary tube electrode using EDM is focused to solve this problem in EDM.

In point, very few research articles found on EDM using rotary tube electrodes. In that list, Nivin V and Arun B K performed EDM with En41b steel using copper and brass rotary tube of diameter 0.8 mm and found optimal setting by adapting grey and Taguchi's techniques [6]. Priyaranjan et al did EDM of AISI tool with copper and brass rotary tube electrode using Taguchi's techniques [7].

Research article pointed by Sanchez making high aspect ratio holes less than 1 mm in the hard material is greatly used [8]. Shuliang et al performed high aspect ratio (23.26) drilling on 5 mm thick C17200 beryllium copper alloy using 200 µm diameter tungsten electrode by µ-EDM and in situ PMEDM. The surface quality of rapidly drilled hole was improved by in situ PMEDM when comparing with µ-EDM [9]. Durso G and Ravasio C analyzed micro EDM drilling of different workpiece materials such as stainless steel-AISI 304, tungsten carbide-WC and Aluminium-AA6062 by employing various electrode materials namely tungsten carbide and brass to evaluate the MRR, TWR, DOC, and TR. Properties of the electrode materials have a significant impact on these indicators [10].

Ferraris E et al conducted high aspect ratio µ-EDM on carbide workpiece using commercially available WC. The authors assessed further using parylene C and SiCN –SiC coated WC electrode. The coated electrode 30% increases high aspect ratio for deep µ-EDM drilling. In point, it improves the shape of the hole and reduces tool wear drastically. Finally, it concludes parylene C coating declares best results for high aspect ratio µ-EDM [11]. Lee C S et al exposed that, tool wear in EDM drilling is high compared to sinking EDM, but it finds great use in the manufacturing of micro-parts. The tool wears rate estimation in EDM drilling was investigated [12].

In this paper, a new attempt is made on EDM by considering rotary brass tube electrode of 300 µm good quality holes at both entry and exit in hard materials such as Ti-6Al-4V. It strongly inspires the advancement in EDM under high aspect ratio drilling of meso-holes. The metallurgical properties of an electrode (brass tube) and a workpiece (Ti-6Al-4V) are tabulated in table 1.

Table 1. Chemical Composition of Workpiece and Tool

Ti-6Al-4V		Brass Tube	
Element	Wt (%)	Element	Wt (%)
Carbon	0.02	Copper	63.57
Aluminium	6.35	Iron	1.08
Vanadium	4.27	Nickel	0.085
Titanium+	88.88	Chromium	0.093
		Zinc +	35.17

2. Experimental details

In this study, the workpiece material was 18 mm thick Ti-6Al-4V grade 5 as per ASTM B348 titanium-based alloy. It is tested to show the high hardness of 33 HRC. The tool materials were commercially available 300 µm brass rotary tube electrode. The entire experiments were conducted using Sparkonix EDM drill – speed II machine. The schematic representation of experimental set up is shown in figure 1. The few important parts of the machine are marked in red colour as 1, 2, 3, 4, 5 namely workpiece, tube electrode, dielectric (deionized water), tank and DRO unit. The DRO unit consists of the key parameter such as current, Gap voltage, on time and off time to control the performance of the machine.

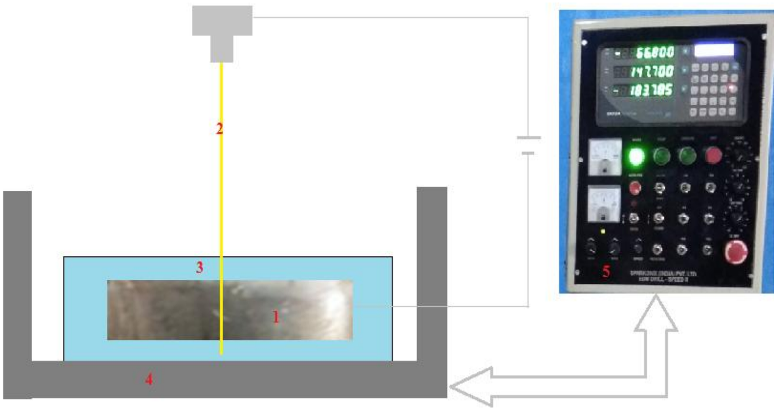

Figure 1. Schematic experimental setup

The 3 level, 4 factor L27 Taguchi's orthogonal layout is employed to perform the experiments. The standard L27 Taguchi's experimental with layout is displayed in table 2. And also EDM parameters and other constant experimental parameters involved in this paperwork are illustrated in table 3. After machining, optical microscope interfaced with imaging software Dewinter material plus 4.5 with 100x magnification lens is used to capture the entry and exit of the machined holes. The taperness [13] and linear wear rate of the machined hole is calculated using the formulae mentioned in equations [1] and equation [2].

Table 2. Experimental Layout

Sl.No.	Current	Gap Voltage	On time	Off time	Taperness (°)	LWR (mm/sec)
1	2	30	6	5	0.0887	1.5263
2	2	30	6	5	0.1318	1.5131
3	2	30	6	5	0.1168	1.5247
4	2	40	8	7	0.0162	7.0833
5	2	40	8	7	0.0252	7.2580
6	2	40	8	7	0.2114	6.3081
7	2	50	10	9	0.0788	13.3962
8	2	50	10	9	0.0936	13.7662
9	2	50	10	9	0.0702	14.3421
10	4	30	8	9	0.2025	2.3518
11	4	30	8	9	0.3672	2.7031
12	4	30	8	9	0.2681	2.4444
13	4	40	10	5	0.4633	5.0898
14	4	40	10	5	0.4291	6.7698
15	4	40	10	5	0.0789	6.6875
16	4	50	6	7	0.1551	20.2385
17	4	50	6	7	0.0571	21.1818
18	4	50	6	7	0.0549	19.6752
19	6	30	10	7	0.1619	10.7914
20	6	30	10	7	0.5202	5.2326
21	6	30	10	7	0.4101	4.1509
22	6	40	6	9	0.0571	18.8679
23	6	40	6	9	0.0734	17.4167
24	6	40	6	9	0.0603	16.6400
25	6	50	8	5	0.529	13.3129
26	6	50	8	5	0.0201	9.9767
27	6	50	8	5	0.0029	6.9480

$$LWR = \frac{LW}{t} \quad (1)$$

$$TA = \tan\left[\frac{(D-d)}{2H}\right] \quad (2)$$

Table 3. EDM parameters and other constant experimental parameters

Dielectric type	Deionised water
Polarity	Negative
Dielectric Pressure	100 kg/cm2
Workpiece	Ti-6Al-4V
Workpiece dimensions	66 mm diameter 18mm thick
Electrode Material	Brass tube
Electrode dimensions	300 µm diameter 400 mm long
Current (A)	2, 4, 6
Gap voltage (V)	30, 40, 50
On time (µs)	6, 8, 10
Off time (µs)	5, 7, 9

3. TOPSIS

In this method, Techniques for Order of Preference by Similarity to Ideal Solution (TOPSIS) is proposed to find best and worst ideal solution for the responses taken [14]. It is observed from table 2, a decision matrix is formed by D_{27x2} which consists of 2 responses and 27 combinations of run in the form a matrix and it is pushed through the following formulae stated in equation [3-9] by assuming suitable weight. Before the end, the calculated CC values are ranked in order to get the best as well as worst ideal solutions. The constructive step by step TOPSIS is built up in figure 2 for easy understanding.

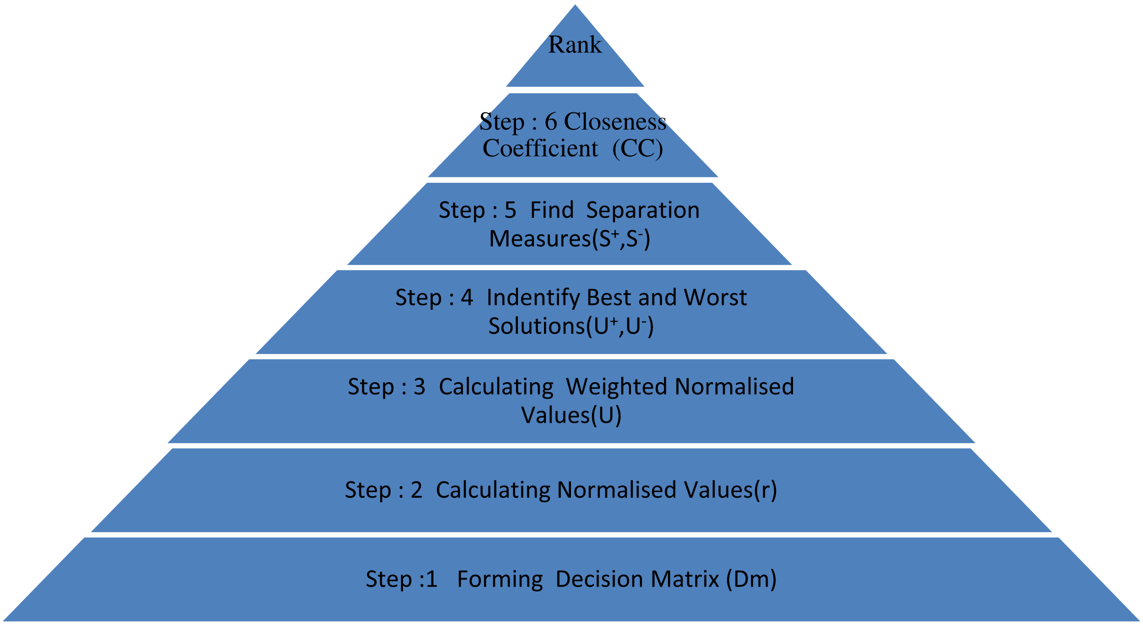

Figure 2. Constructive step by step of TOPSIS

$$r_{ij} = \frac{y_{ij}}{\sqrt{\sum_{i=1}^{m} y_{ij}^2}} \quad j=1,2,\ldots,n. \tag{3}$$

$$U = w_j r_{ij} \tag{4}$$

$$U^+ = (U_1^+ U_2^+, \ldots . U_n^+) \text{ Maximum values,} \tag{5}$$

$$U^- = (U_1^- U_2^-, \ldots . U_n^-) \text{ Minimum values} \tag{6}$$

$$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(U_{ij} - U_J^+\right)^2} \tag{7}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(U_{ij} - U_J^-\right)^2} \tag{8}$$

$$CC = \frac{S_i^-}{(S_i^+ + S_i^-)} \tag{9}$$

4. Results and Discussions

Table 3 shows the normalized, weighted normalized and separation measures and closeness coefficient values and rank for each experimental run based on L27 Taguchi's orthogonal array. These values have been calculated based on the previous sections. In point, for the experimental run 27 shows rank 1, the highest CC value is obtained at the parametric setting current 6A, gap voltage 50 V, on time 8µs and off time 5µs. The experimental run 27 provides the best ideal solution having CC value is 1. At this run, the calculated value of taperness is 0.0029º and linear wear rate is 6.948 mm/sec. The experimental run 2 shows rank 27, the lowest CC value is observed at the parametric setting current 2A, Gap voltage 30 V, on time 6 µs and off time 5µs. the experimental run 2 provides the worst ideal solutions having CC value is 0. The taperness of 0.1318° and linear wear rate of 1.5263 mm/sec are calculated at this setting. The Taguchi method is adopted to get main effects plot in Minitab software. The main effects plot graph for taperness shown in figure 3. The main effects plot for linear wear rate is illustrated in figure 4.

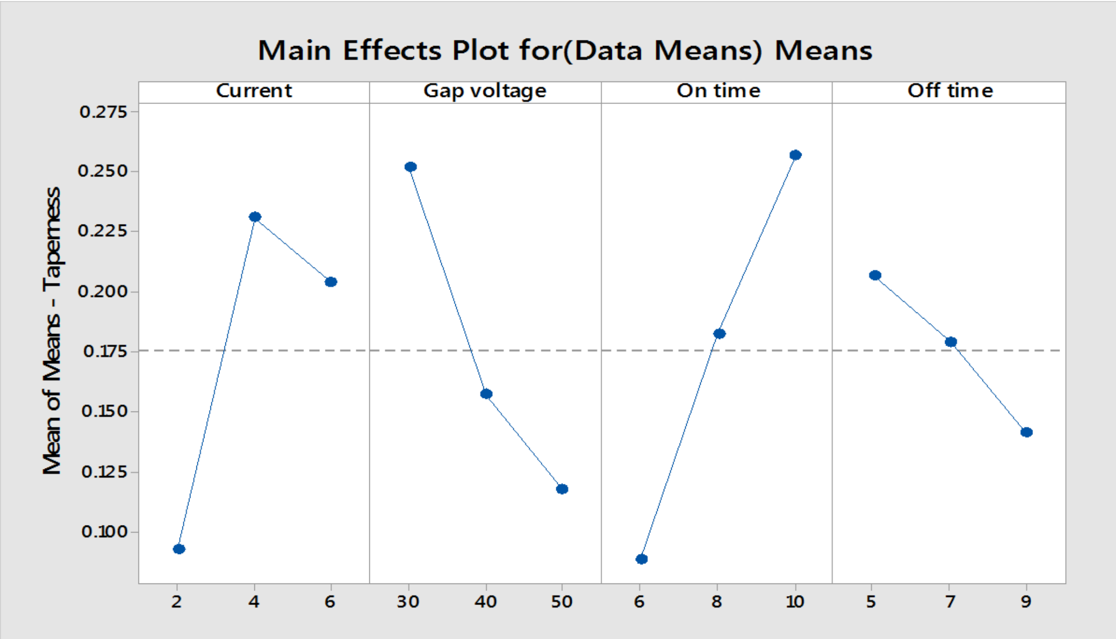

Figure 3. Main effects plot for taperness

Table 4. Normalized, Weighted Normalized and Separation Measures and Closeness Coefficient values and Rank

Sl.No.	Normalized values		Weighted normalized values		S+	S-	CC	Rank
	Taperness	LWR	Taperness	LWR				
1	0.0714	0.0257	0.0428	0.0103	0.0414	0.0001	0.0021	25
2	0.1060	0.0255	0.0636	0.0102	0.0622	0.0000	0.0000	27
3	0.0940	0.0257	0.0564	0.0103	0.0550	0.0001	0.0014	26
4	0.0130	0.1193	0.0078	0.0477	0.0064	0.0375	0.8539	3
5	0.0203	0.1222	0.0122	0.0489	0.0108	0.0387	0.7823	8
6	0.1701	0.1062	0.1020	0.0425	0.1006	0.0323	0.2429	16
7	0.0634	0.2256	0.0380	0.0902	0.0366	0.0800	0.6860	11
8	0.0753	0.2318	0.0452	0.0927	0.0438	0.0825	0.6534	12
9	0.0565	0.2415	0.0339	0.0966	0.0325	0.0864	0.7268	10
10	0.1629	0.0396	0.0978	0.0158	0.0964	0.0056	0.0554	22
11	0.2954	0.0455	0.1773	0.0182	0.1759	0.0080	0.0436	24
12	0.2157	0.0412	0.1294	0.0165	0.1280	0.0063	0.0467	23
13	0.3727	0.0857	0.2236	0.0343	0.2222	0.0241	0.0978	19
14	0.3452	0.1140	0.2071	0.0456	0.2057	0.0354	0.1468	18

15	0.0635	0.1126	0.0381	0.0450	0.0367	0.0349	0.4872	14
16	0.1248	0.3408	0.0749	0.1363	0.0735	0.1261	0.6319	13
17	0.0459	0.3567	0.0276	0.1427	0.0262	0.1325	0.8351	4
18	0.0442	0.3313	0.0265	0.1325	0.0251	0.1223	0.8297	5
19	0.1303	0.1817	0.0782	0.0727	0.0768	0.0625	0.4488	15
20	0.4185	0.0881	0.2511	0.0352	0.2497	0.0251	0.0912	20
21	0.3299	0.0699	0.1980	0.0280	0.1966	0.0178	0.0829	21
22	0.0459	0.3177	0.0276	0.1271	0.0262	0.1169	0.8171	6
23	0.0591	0.2933	0.0354	0.1173	0.0340	0.1071	0.7589	9
24	0.0485	0.2802	0.0291	0.1121	0.0277	0.1019	0.7862	7
25	0.4256	0.2242	0.2554	0.0897	0.2540	0.0795	0.2383	17
26	0.0162	0.1680	0.0097	0.0672	0.0083	0.0570	0.8729	2
27	0.0023	0.1170	0.0014	0.0468	0.0000	0.0366	1.0000	1

From figure 3 main effects plot for input parameters current, gap voltage, on time and off time on taperness. The current increases from 2A to 4A taperness increases, but for adding current from 4A to 6A taperness angle is decreased. It is recorded graphically by increasing gap voltage and off time reduction in taperness. But on time shows that, increases in taperness by increasing it. From figure 4 main effects plot for input parameters current, gap voltage, on time and off time on linear wear rate. The current and gap voltage is directly proportional to the LWR; it increases to increase the linear wear rate. The on time increases from 6 µs to 8 µs reduction in linear wear rate and further from 8 µs to 10 µs increases in linear wear rate. The last of all, off time increases from 5 µs to 7 µs reduction in LWR after from 7 µs to 9 µs constant LWR was registered.

The scatter plot graph for taperness is captured in figure 5. It indicates the taperness values for all the experimental run. The area plot graph for LWR is coined in figure 6. It clears the lowest tool wear is 1.5131 mm/sec for run 2. The higher LWR is 21.1818 mm/sec observed for the experimental run 17. The main effects plot graph LWR viewed in figure 4.

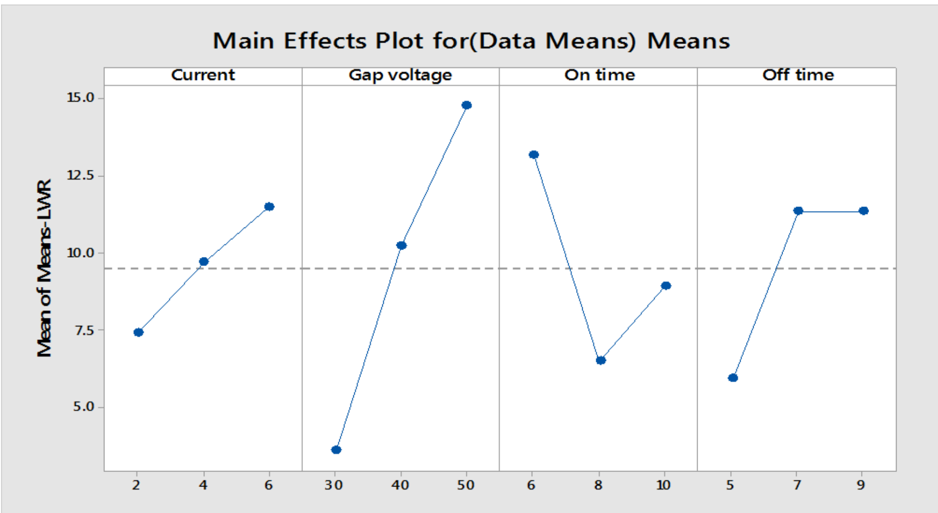

Figure 4. Main effects plot for Linear Wear Rate

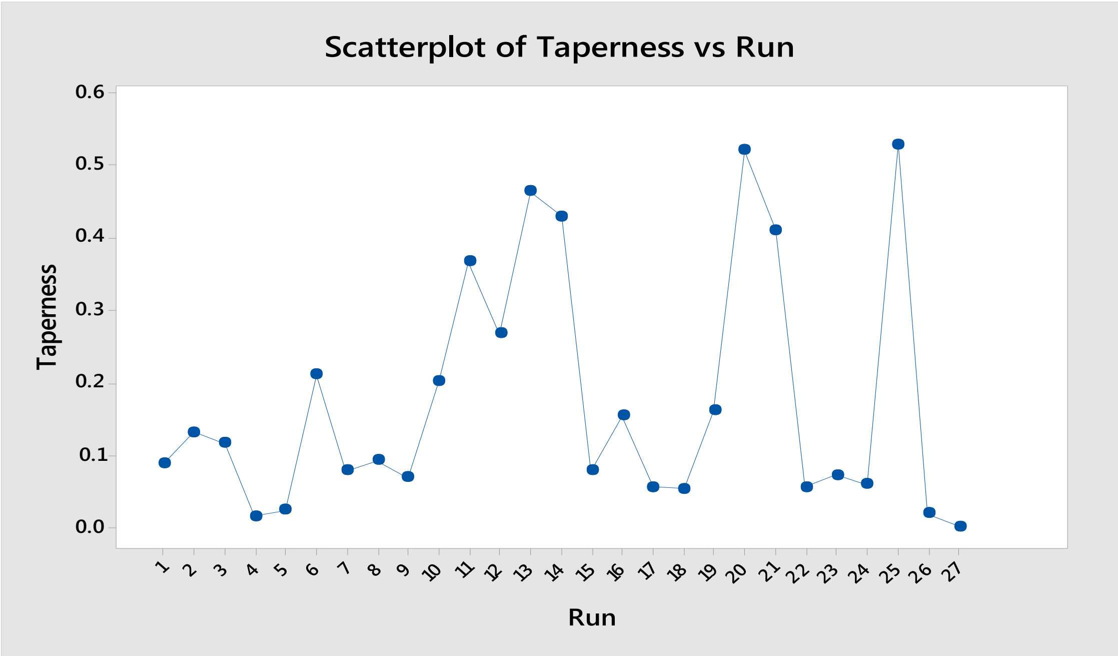

Figure 5. Scatter plot of Taperness

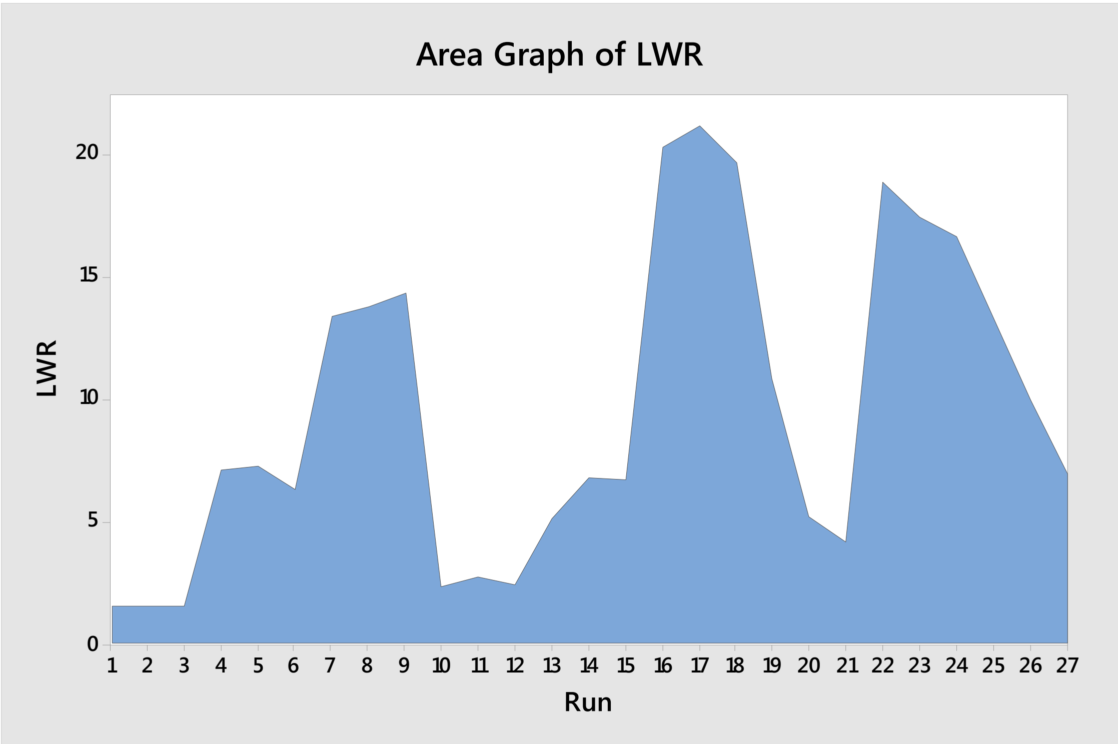

Figure 6. Area plot of LWR

4.1. Micro-analysis

In order to perform micro-analysis study, the SEM images of the run 27 both entry and exit of the machined holes were made. The SEM image of the micro hole at entry is viewed in figure 7. It demonstrates that, good circularity appearance on the top with a slight burr on the surface of side walls.

Figure 7. Machined hole entry for setting no.27

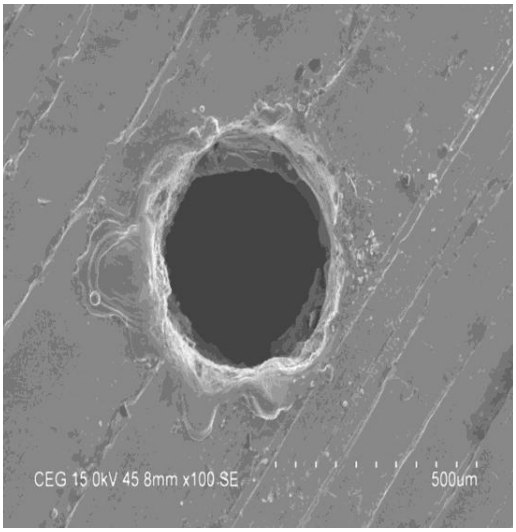

Figure 8. Machined hole exit for setting no.27

In the similar fashion, the SEM image of the micro hole at the exit is viewed in figure 8. It also clears that, good circularity appearance of a hole at exit face. On the other hand run 2, both entry and exit of the machined holes are also photographed in SEM.

Figure 9 photograph pictorially confirm, the SEM image of the machined hole at entry gives very good circularity. Figure 10 shows that the exit hole SEM image rotary brass tube EDM for run 2. But seen from figure10 elliptical shape hole was observed with excess diameter. It is concluded from the SEM study the run 27 provides the best taperness and run 2 grants the worst taperness. The result confirms the same and its adding noteworthy information to the experimental results.

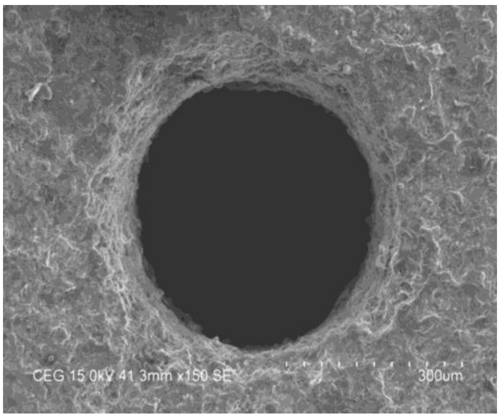

Figure 9. Machined hole entry for setting no.2

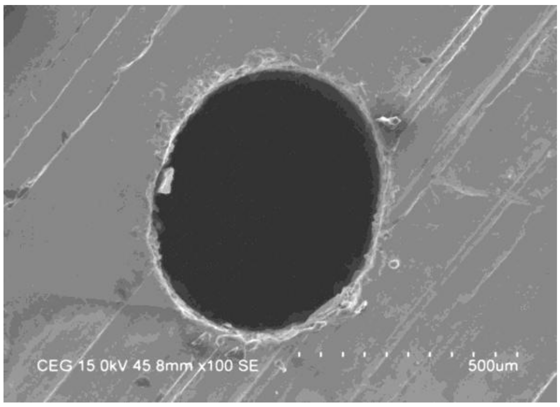

Figure 10. Machined hole exit for setting no.27

5. Conclusion

The paper has presented the use of the TOPSIS method based on the L27 Taguchi's experimental layout for analyzing taperness and linear wear rate in the EDM process using commercial brass rotary tube electrode. The main conclusions were posted as follows:

- The detailed analysis shows that, high current, strong gap voltage, moderate pulse on time, and low pulse off time provides minimum taperness of 0.0029º can be recorded. The optimum EDM parameters obtained with the input current 6A, gap voltage 50V, on-time 8µs and off-time 5µs.
- The investigation indicates the minimum linear wear rate of 1.5131 mm/sec can be calculated for the EDM parameters has current 4A, gap voltage 50V, on-time 6µs and off-time 7µs.
- The almost zero degree taperness obtained in this work with very less tool wear, Ii is further to study the surface integrity analysis of all the machined holes by using SEM to build numerical relationship for taperness with other performance characteristics such as overcut, recast layer thickness, material removal rate, machining time, circularity error and so on.
- The research work is intended to finds applications in micro part fabrication, micro mould making, creating complex shapes, forming dies, cavities and even 3D structure by integrating with WEDM processes. The small size holes directly made on turbine blades for cooling purpose.

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