IOP Conf. Series: Materials Science and Engineering **377** (2018) 012202 doi:10.1088/1757-899X/377/1/012202

Parametric Optimization of Micro-EDM Process during Micro-hole Machining on Ti-6Al-4V using WASPAS Method

A. P. Tiwary[1*], P. P. Das[1], S. Chakraborty[1], B. B. Pradhan[1], B. Bhattacharyya[2]

[1.] Mechanical Engineering Department, SMIT, Majitar, Sikkim -737136

[2.] Production Engineering Department, Jadavpur University, Kolkata-700032

* aptiwary@gmail.com

Abstract: Micromachining of Ti-6Al-4V is extremely difficult using conventional machining processes, especially during machining of micro-cavities and micro-through holes as it exhibits poor machinability. Amongst various non-conventional machining processes, micro-electro discharge machining (micro-EDM) has been recognized to be most suitable machining method for micromachining of Ti-6Al-4V. However, micro-EDM is an extremely complicated micromachining process, influenced by several process parameters. In present research investigation, an attempt has been made to select the optimal combination of micro-EDM process parameters such as pulse on time (T_{on}), peak current (I_p), flushing pressure (F_p) and type of dielectric, which greatly influence the micro-EDM process during machining of Ti-6Al-4V using WASPAS (Weighted Aggregated Sum Product ASsessment) method. In a series of planned experimental runs, micro-through hole machining has been carried out during experimental investigation and a model for multi-criteria decision making (MCDM) has been successfully developed in order to identify the optimum process parameters in micro-EDM process, which influence several machining criterion such as material removal rate (MRR), tool wear rate (TWR), overcut (OC) and taper. WASPAS method has been applied to obtain the optimal process parameters from the sets of various combinations of process parameters in order to achieve maximum MRR and minimum TWR, OC and taper during machining of Ti-6Al-4V. The obtained optimal process parametric combination has been experimentally validated and a significant improvement of 30.87% is observed.

1. Introduction

Ti-6Al-4V is the most extensively used titanium alloy in different fields of engineering. It features good machinability and excellent physical and mechanical properties such as highly corrosion resistant, high temperature resistant, high strength-to-weight ratio, biocompatibility etc. Ti-6Al-4V alloy offers the best outstanding performance for a variety of weight reduction applications in aerospace, automotive, biomedical and marine equipment [1-3]. Due to the above mentioned classical properties and its versatile range of applications in various engineering fields, micromachining of Ti-6Al-4V has become the recent area of research and are of immense need in the precision manufacturing industries. However, micromachining of Ti-6Al-4V is enormously challenging using conventional machining processes, especially during the drilling of micro-cavities and micro-through holes as it exhibits poor machinability. In order to overcome the limitations of conventional machining processes in machining of Ti-6Al-4V, a non-conventional machining processes such as micro-electro discharge machining (micro-EDM) has been recognized to be most suitable machining processes for micromachining of Ti-6Al-4V. Micro-EDM is a thermo-electric micromachining process in which there is no involvement of mechanical forces during machining as tool electrode and workpiece are not in direct contact. The material is eroded by a sequence of pulsed spark discharges formed at the small inter electrode gap between tool electrode and workpiece, both immersed in a dielectric medium. This process is used to machine any electrical conductive material regardless of their strength, toughness and hardness. Due to the various advantages such as very insignificant process forces during machining, excellent repeatability, low set-up cost, high precision, high aspect ratio and considerable design freedom, micro-EDM process has been gaining popularity in the precision manufacturing world day by day [4]. Furthermore, the machined surface is burr free and surface finish is reasonably fine. Micro-EDM process have been successfully utilized to produce several micro parts such as micro-nozzles, micro-pins and micro-cavities [5-9].

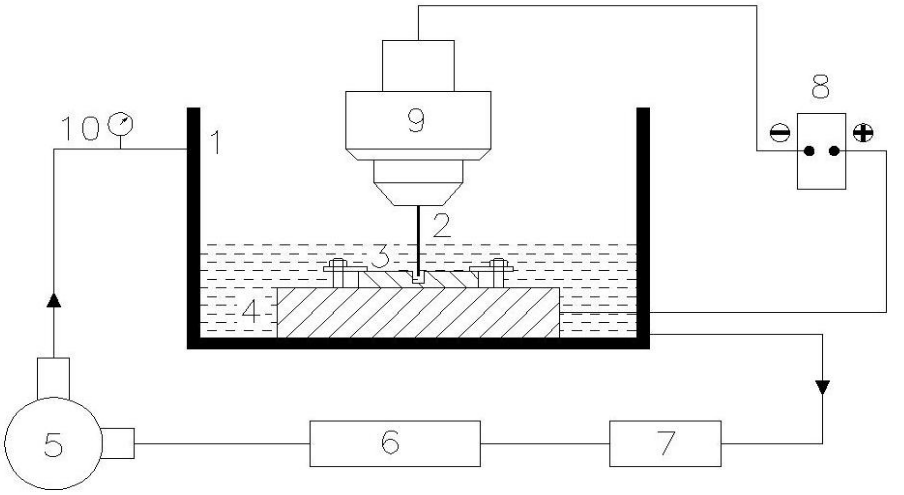
Although there are several benefits of micro-EDM process in micromachining applications, however, it is an extremely complicated process. The numerous micro-EDM process parameters like pulse-on-time (T_{on}), peak current (I_p), flushing pressure (F_p) and type of dielectric used during machining influence the machining performance essentially. Therefore, judicious selection of micro-EDM process parametric combination becomes very important and equally challenging for obtaining higher material removal rate (MRR) and lower of tool wear rate (TWR), overcut (OC), taper each for increasing machining efficiency with geometrically accurate micro-parts.

Many research for improving the machining efficiency of micro-EDM process have been undertaken by the researchers in the recent past. However, quite a few literatures are available on the optimization of various influential micro-EDM process parameters. Bigot et al. [10] optimized the parameters of micro-EDM process to achieve higher MRR and surface finish on tool steel P20. Pradhan and Bhattacharyya [11] modeled the micro-EDM process using RSM and ANN to determine the optimal setting of process parametric combination. Somashekhar et al. [12] developed a model for MRR optimization in micro-EDM using artificial neural network and genetic algorithm. Mustafa et al. (2013) optimized the micro-EDM process parameters during drilling of Inconel 718 using grey relational analysis for multi performance characteristics [13]. Attempts have also been made to optimize micro-EDM process parameters using RSM based multi-objective optimization, fuzzy-TOPSIS and principal component analysis [3, 14, 15]. From the literature, it is evident that most of the researches have focused on the optimization of few important micro-EDM process parameters. However, type of dielectric used during machining has not been considered along with other influential micro-EDM process parameters in available literature. Hence, selection of suitable process parametric combination of micro-EDM process is not fully explored and still challenging as it varies from material to material and each workpiece and tool combination. Therefore, an attempt has been made in the present research to identify optimal combination of micro-EDM process parametric setting including type of dielectric used during machining, which can yield the best machining performance. A systematic and simple framework for optimization of various important micro-EDM process parameters such as I_p, T_{on},V_g, F_p and type of dielectric has been proposed in order to improve the machining characteristics of machined micro-through hole such as MRR, TWR, OC and taper during micro-hole machining on Ti-6Al-4V using WASPAS (Weighted Aggregated Sum Product ASsessment) method.

2. Experimental planning

In the present research work, the objective was to generate micro through-holes of diameter 300 μm on a Ti-6Al-4V sheet of 1 mm thickness using brass electrode. For each set of experiments, new and identical micro-tools made of brass (Φ 300 μm) with specially designed micro-tool holding attachment were used with positive polarity. The experiments were carried out on a EDM (Model S50 ZNC), manufactured by Sparkonix, India, attached with manual controller.

Schematic of micro-EDM experimental set-up is shown in Figure 1. The several influencing micro-EDM process parameters such as; I_p, T_{on} and F_p were considered as variable parameters while keeping other machining parameters constant. The experiments were conducted separately using two different types of dielectrics like DEF-92 and pure deionized water. In total, twenty-four experimental runs were conducted and the corresponding machining responses were recorded and utilized for analyses. The detailed experimental conditions are shown in Table 1. Table 2 enlists the machining parameters along with their levels.



1. Machining chamber filled with dielectric medium, 2. Micro-tool electrode, 3. Workpiece, 4. Work table, 5. Dielectric pump, 6. Dielectric reservoir, 7. Filter, 8. Pulsed DC power supply, 9. Servo control, 10. Pressure gauge

Figure 1: Schematic of EDM micromachining experimental set-up

Table 1: Experimental condition for micro through hole machining on Ti-6Al-4V.

Experimental condition	**Description**
Work piece material	Ti-6Al-4V
Tool Material and size	Brass, Φ 300 μm
Dielectric	DEF-92 (EDM oil), Deionized water (Conductivity 9.6 µS)
Polarity	Positive workpiece: '+ve', tool: '-ve')
Peak current (A)	0.5 to 2.0
Pulse on time (μs)	1 to 12
Flushing pressure (kg/cm^2)	0.15 to 0.30
Gap voltage (V_g)	50

Table 2: Micro-EDM process parameters and their levels for micro- through hole machining on Ti-6Al-4V.

Process Parameters	Levels			
	Level 1	Level 2	Level 3	Level 4
Ton	1	4	8	12
Ip	0.5	1	1.5	2
Fp	0.15	0.2	0.25	0.3
Dielectric type	DEF-92	DI Water	-	-

In the present research investigation, several micro-EDM process response considered during machining of micro-through holes on Ti-6Al-4V were MRR, TWR, OC and taper. These machining responses were calculated for each corresponding experimental run based on experimental scheme. Using weight difference method, MRR and TWR were calculated. Weight of each workpiece and tool before and after machining were taken by using a precision weighing balance (METTLER TOLEDO, Switzerland) having least count of 0.01mg. The difference in weight of workpiece and tool per unit machining time yielded MRR and TWR respectively. The diameters of each micro-hole at entry and exit have been measured using optical precision measuring microscope (LEICA DM2500) at 10×

magnification. The dimensions of the machined micro-holes were measured and recorded. Diametral OC and Taper were calculated using following relations (1) and (2) respectively.

$$OC = D_{Entry} - D_{Tool} \quad (1)$$

where, D_{Entry} and D_{Tool} are the diameters of micro-hole at entry and tool electrode respectively.

$$Taper = \frac{D_{Entry} - D_{Exit}}{2L} \quad (2)$$

where, D_{Entry} and D_{Exit} are diameters at entry and exit and L is the length of the micro-hole.

The experimental planning consists of various the process parametric combinations along with their corresponding machining responses are enlisted in Table 3. These responses were further employed for optimization of micro-EDM process parameters during micro-through machining on Ti-6Al-4V using WASPAS method.

Table 3: Experimental results

Exp. No.	Micro-EDM process parameters				Micro-EDM process response			
	T_{on} (µs)	I_p (A)	F_p ($kgcm^{-2}$)	Dielectric type	MRR (mg/min)	TWR (mg/min)	OC (mm)	Taper
1	8	0.5	0.15	DEF-92	0.0157	0.0084	0.0532	0.0155
2	8	1	0.15	DEF-92	0.0125	0.0096	0.0654	0.0134
3	8	1.5	0.15	DEF-92	0.0146	0.0149	0.0794	0.0116
4	8	2	0.15	DEF-92	0.0166	0.0247	0.0892	0.0829
5	1	0.5	0.15	DEF-92	0.0195	0.0072	0.045	0.014
6	4	0.5	0.15	DEF-92	0.014	0.0127	0.0666	0.0227
7	8	0.5	0.15	DEF-92	0.0147	0.0235	0.0792	0.0302
8	12	0.5	0.15	DEF-92	0.0078	0.0076	0.0456	0.0061
9	8	0.5	0.15	DEF-92	0.0098	0.0061	0.041	0.0017
10	8	0.5	0.2	DEF-92	0.0127	0.0122	0.1055	0.0258
11	8	0.5	0.25	DEF-92	0.0087	0.0068	0.0392	0.0012
12	8	0.5	0.3	DEF-92	0.0062	0.006	0.0375	0.0015
13	8	0.5	0.15	DI Water	0.0165	0.0026	0.0124	0.0009
14	8	1	0.15	DI Water	0.0983	0.0895	0.0532	0.002
15	8	1.5	0.15	DI Water	0.0327	0.0336	0.0782	0.0047
16	8	2	0.15	DI Water	0.0314	0.005	0.1038	0.0332
17	1	0.5	0.15	DI Water	0.0311	0.0096	0.0398	0.0134
18	4	0.5	0.15	DI Water	0.0216	0.0053	0.034	0.0116
19	8	0.5	0.15	DI Water	0.0175	0.0084	0.0538	0.0047
20	12	0.5	0.15	DI Water	0.065	0.0099	0.0514	0.0227
21	8	0.5	0.15	DI Water	0.0172	0.0016	0.0334	0.0029
22	8	0.5	0.2	DI Water	0.0528	0.0164	0.0584	0.011
23	8	0.5	0.25	DI Water	0.0293	0.0059	0.0613	0.0148
24	8	0.5	0.3	DI Water	0.05	0.0227	0.0631	0.0108

3. Methodology

3.1. WASPAS method

Every MCDM problem starts with the following decision/evaluation matrix:

$$\bar{X} = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix} \quad (3)$$

where, m is the number of candidate alternatives, n is the number of evaluation criteria and xij is the performance of ith alternative with respect to j th criterion.

The WASPAS method, which is a unique combination of two well-known MCDM approaches, i.e. weighted sum model (WSM) and weighted product model (WPM). Firstly, it requires linear normalization of the decision matrix elements using the following two equations:

For beneficial criteria,

$$\bar{x}_{ij} = \frac{x_{ij}}{max_i \, x_{ij}} \quad (4)$$

For non-beneficial criteria,

$$\bar{x}_{ij} = \frac{min_i \, x_{ij}}{x_{ij}} \quad (5)$$

where, $\bar{x}_{ij}$ is the normalized value of x_{ij} .

In WASPAS method, a joint criterion of optimality is sought based on two criteria of optimality. The first criterion of optimality, i.e. criterion of a mean weighted success is similar to WSM method. It is a popular and well accepted MCDM approach applied for evaluating a number of alternatives in terms of a number of decision criteria. Based on WSM method [16, 17], the total relative importance of i^{th} alternative is calculated as follows:

$$Q_i^{(1)} = \sum_{j=1}^{n} \bar{x}_{ij} \, w_j \quad (6)$$

where w_j is weight (relative importance) of significance (weight) of jth criterion. On the other hand, according to WPM method [17, 18], the total relative importance of ith alternative is computed using the following expression:

$$Q_i^{(2)} = \prod_{j=1}^{n} \bar{x}_{ij}^{\,w_j} \quad (7)$$

A joint generalized criterion of weighted aggregation of additive and multiplicative methods is then proposed as follows [19, 20]:

$$Q_i = 0.5 Q_i^{(1)} + 0.5 Q_i^{(2)}$$
$$= 0.5 \sum_{j=1}^{n} \bar{x}_{ij} \, w_j + 0.5 \prod_{j=1}^{n} \bar{x}_{ij}^{\,w_j} \quad (8)$$

In order to have increased ranking accuracy and effectiveness of the decision making process, in WASPAS method, a more generalized equation for determining the total relative importance of i[th] alternative is developed as below [21, 22]:

$$Q_i = \lambda Q_i^{(1)} + (1-\lambda) Q_i^{(2)}$$
$$= \lambda \sum_{j=1}^{n} \bar{x}_{ij}\, w_j + (1-\lambda) \prod_{j=1}^{n} \bar{x}_{ij}^{\,w_j} \quad (\lambda = 0, 0.1, 0.2, \ldots) \tag{9}$$

Now, the candidate alternatives are ranked based on the Q values, i.e. the best alternative would be that one having the highest Q value. When the value of λ is 0, WASPAS method is transformed to WPM, and when λ is 1, it becomes WSM method. Till date, WASPAS method has very few successful applications, only in location selection problems [23] and civil engineering domain [24, 25].

4. Results and Discussions

4.1. WASPAS Method

WASPAS is carried out for the solution of complicated problems having interrelationship among the selected performance characteristics. It is also an effective tool to solve multi criteria decision making problems. In order to exploit the above-mentioned advantages, this method has been utilized to identify the optimal parametric combination of micro-EDM process parameter namely Ton, I_p, F_p and type of dielectric used during machining. As discussed above MRR, TWR, OC and taper were chosen as the control parameters for the mirco-EDM process of which MRR is only the larger-the better type (beneficial criteria) whereas the other parameters are of lower-the-better type (non-beneficial criteria).

Now based on the type of response characteristics the values are normalized using equation (4) and (5) to a range between 0 and 1 so as to make the data dimensionless and comparable and are presented in table 4. From these normalized values the corresponding WSM ($Q^{(1)}$) and WPM ($Q^{(2)}$) scores are calculated as shown in table 4 using equation (6) and (7) respectively. The weights for the different criteria are taken from Tiwary et al. [14] which are evaluated from using fuzzy logic based on experts' opinion. The weights considered are 0.875 for pulse-on-time, 0.15 for peak current, 0.24 for flushing pressure, and 0.24 for dielectric fluid. Finally, the WASPAS score (Q) is calculated based on equation (6) and (7) where the value of λ is taken as 0.5 so as to give equal weightage to both WSM and WPM scores respectively. The calculated values of WASPAS score are shown in table 4. The highest score indicates that experiment run to be the best among all. From the table it can be seen that the highest score is for experiment number 14 followed by 13 which indicates these to be the most preferred whereas, experiment number 10 is the least preferred.

4.2. Response table for WASPAS score

The response table for WASPAS score is presented in Table 5. It is obtained by averaging the WASPAS score obtained for each input parameters at its corresponding level. The last column indicates the difference of maximum and minimum value of the obtained score for each input parameters. The highest value of the four input parameters shows that peak current is the most influencing micro-EDM process parameter and affects significantly on the multi-performance characteristics among all other process parameters. The best optimal combination obtained for the response table shows that pulse-on-time and flushing pressure must be set at level 4 whereas peak current and dielectric type should be maintained at level 2 respectively.

Figure 2 shows the response graph for the calculated WASPAS score for the input machining parameters. It can be seen for the graph that the highest peak and slope for peak current signifies it to be more influencing parameter followed by dielectric type, pulse-on-time and flushing pressure which also supports the above observations made.

Table 4: Normalized Data and WASPAS results

Exp. No.	Normalized values				$Q^{(1)}$	$Q^{(2)}$	Q
	MRR	TWR	OC	Taper			
1	0.1597	0.1905	0.2331	0.0581	0.2382	0.0558	0.1470
2	0.1272	0.1667	0.1896	0.0672	0.1979	0.0442	0.1211
3	0.1485	0.1074	0.1562	0.0776	0.2022	0.0468	0.1245
4	0.1689	0.0648	0.139	0.0109	0.1935	0.0295	0.1115
5	0.1984	0.2222	0.2756	0.0643	0.2885	0.0736	0.1811
6	0.1424	0.126	0.1862	0.0396	0.1977	0.041	0.1194
7	0.1495	0.0681	0.1566	0.0298	0.1858	0.0349	0.1104
8	0.0793	0.2105	0.2719	0.1475	0.2016	0.0398	0.1207
9	0.0997	0.2623	0.3024	0.5294	0.3262	0.0701	0.1982
10	0.1292	0.1311	0.1175	0.0349	0.1693	0.0329	0.1011
11	0.0885	0.2353	0.3163	0.75	0.3686	0.0683	0.2185
12	0.0631	0.2667	0.3307	0.6	0.3186	0.0496	0.1841
13	0.1679	0.6154	1	1	0.7192	0.1951	0.4572
14	1	0.0179	0.2331	0.45	1.0416	0.3184	0.6800
15	0.3327	0.0476	0.1586	0.1915	0.3823	0.1045	0.2434
16	0.3194	0.32	0.1195	0.0271	0.3627	0.0784	0.2206
17	0.3164	0.1667	0.3116	0.0672	0.3928	0.1104	0.2516
18	0.2197	0.3019	0.3647	0.0776	0.3437	0.0943	0.2190
19	0.178	0.1905	0.2305	0.1915	0.2856	0.0814	0.1835
20	0.6612	0.1616	0.2412	0.0396	0.6702	0.1735	0.4219
21	0.175	1	0.3713	0.3103	0.4667	0.1295	0.2981
22	0.5371	0.0976	0.2123	0.0818	0.5552	0.1548	0.3550
23	0.2981	0.2712	0.2023	0.0608	0.3647	0.0992	0.2320
24	0.5086	0.0705	0.1965	0.0833	0.5228	0.1386	0.3307

Table 5: Response table for WASPAS score

Process Parameters	Levels				Max - Min	Rank
	Level 1	Level 2	Level 3	Level 4		
Ton	0.2164	0.1692	0.2398	**0.2713**	0.1021	III
Ip	0.2294	**0.4006**	0.184	0.1661	0.2345	I
Fp	0.2338	0.2281	0.2253	**0.2574**	0.0321	IV
Dielectric type	0.1448	**0.3244**			0.17	II

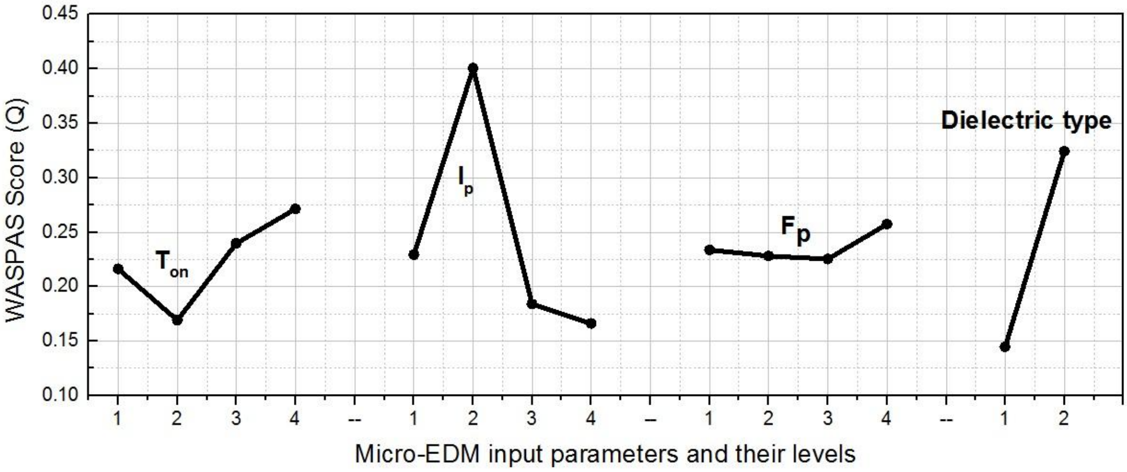


Figure 2: Response graph for WASPAS score

4.3. Test experiment

The obtained results are further verified with an experimental run by machining a micro-hole on Ti-6Al-4V sheet at the optimal parametric combination ie. pulse-on-time on 12µs, peak current as 1.0 A, flushing pressure as 0.30 kgcm^{-2} using deionized water dielectric fluid. The experimental values for MRR, TWR, OC and taper obtained as 0.0675mg/min, 0.0056 mg/min, 0.0365mm and 0.0025 respectively. The predicted WASPAS score can also be calculated using Equation 10.

$$W_p = W_m + \sum_{i=1}^{N} (\overline{W}_i - W_m) \tag{10}$$

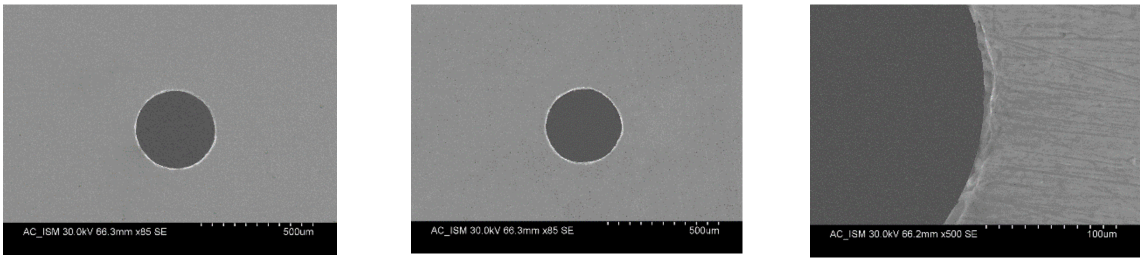
where, W_p is the predicted WASPAS score, W_m is the mean WASPAS score for all the 24 experiments, $\overline{W_i}$ is the mean WASPAS score of the corresponding optimal i^{th} response and N is the total number of input parameters.

The experimental result of test experiment has been compared with the closest process parametric setting i.e. of experimental run 20 within the considered set of experiments enlisted in Table 3. Table 6 shows the comparison between the considered experimental run and the obtained values of response parameters. It can be seen from the table that using the proposed approach, the MRR has significantly increased from 0.065mg/min to 0.0675mg/min, the rate of tool wear has decreased from 0.0099mg/min to 0.0056mg/min. Whereas, the overcut and taper has also decreased from 0.0514mm and 0.0227 to 0.0365mm and 0.0025 respectively. As seen from the table, the experimental test run shows a significant improvement in the WASPAS score as compared to the initial experiment.

Table 6: Comparison table for Initial and optimum input parameters

Levels	First taken machining parameters	Optimum machining parameters	
	T_{on}= 12µs, I_p= 0.5A, F_p= 0.15 kgcm^{-2} and Dielectric type =DI Water	T_{on}= 12µs, I_p= 1.0A, F_p= 0.30 kgcm^{-2} and Dielectric type =D I Water	
		Predicted	Experimental
MRR (mg/min)	0.065		0.0675
TWR (mg/min)	0.0099		0.0056
OC (mm)	0.0514		0.0365
Taper	0.0227		0.0025
WASPAS score	0.4219	0.5499	0.5859
% Improvement		30.33	38.87

Figure 3 shows the SEM micrographs of entry (a), exit (b) and (c) at higher magnification of micro-through hole machined at the multi-objective optimal parametric setting. From these figures, it is evident that profile, topography and white-layer of the machined micro-through hole at optimal parametric setting is quite adequate, which upholds the fact that this achieved optimal process parametric setting can be used to machine geometrically improved micro-through holes on Ti-6Al-4V.



(a) (b) (c)

Figure 3: SEM micrograph of micro-hole (a) entry, (b) exit and (c) at higher magnification of micro-through hole machined at optimal parametric combination i.e., 12μs/1.0A/50V/0.30 $kgcm^{-2}$

5. Conclusion

Micro-electro-discharge machining on Ti-6Al-4V was carried out in present experimental investigation. The experimentations were carried out by varying several important micro-EDM process parameters and the machining responses were observed. To determine the optimum process parameters and their combination for machining on Ti-6Al-4V, WASPAS method was utilized. Following conclusion may be drawn from the modular research:

(i) A robust model for multi-criterion decision making has been successfully developed in order to identify the optimum process parametric combination of micro-EDM process, which greatly influences several machining criterion such as MRR, TWR, OC and taper.

(ii) Based on the analysis of WASPAS score, the optimal machining performance for the micro-through hole machining on Ti-6Al-4V has been identified as 12 μs of T_{on} (level 4), 1.0A of I_p (level 2), 0.3 kg/cm^2 F_p (level 4) using deionized water dielectric.

(iii) Further analysis has indicated that peak current is the most important micro-EDM process parameter and affects significantly on the multi-performance characteristics among all other process parameters.

(iv) The order of micro-EDM process parameters considered in the present study in terms of their importance has been observed as follows: peak current, type of dielectric, pulse-on-time and flushing pressure with their corresponding WASPAS score as 0.2345, 0.17, 0.1021 and 0.0321 respectively.

(v) The obtained optimal process parametric setting has shown a significant improvement of 30.87% in combined effect of micro-EDM process response. The developed framework can be utilized to select the optimal combination from various sets of process parametric combinations of micro-EDM process.

Thus the outcome of this research can be beneficial to the micro manufacturing industries and other researches to improve the precision and geometrical accuracy of the machined through micro-hole on Ti-6Al-4V.

References

[1]. Pradhan B B, Masanta M, Sarkar B R, Bhattacharyya B 2009 Investigation on electro-discharge micromachining of Titanium super alloy. *Int J Adv Manuf Technol* (11-12): 1094-1106.
[2]. Pradhan B B, Bhattacharyya B 2008 Improvement in microhole machining accuracy by polarity changing technique for microelectrode discharge machining on Ti-6Al-4V. *Proc. I Mech E Part B: J. Engineering Manufacture* 222 (2): 163-173.
[3]. Tiwary A. P., Pradhan B. B., Bhattacharyya B 2015 Study on the influence of micro-EDM process parameters during machining of Ti–6Al–4V superalloy. *Int J of Adv Manuf Tech* 76(1): 151-160.
[4]. Liu K, Lauwers B, Reynaerts D 2010 Process capabilities of Micro-EDM and its applications. *Int J Adv Manuf Technol*. 47: 11–19.
[5]. Lim H S, Wong Y S, Rahman M, Edwin Lee M K 2003 A study on the machining of high-aspect ratio microstructure using micro-EDM. *J. Mater Process Technol* 140: 318-325.
[6]. Masaki T, Kawata K, Masuzawa T 1990 Micro electro-discharge machining and its applications. *Proceedings IEEE Micro Electro Mechanical Systems, Japan* : 21–26.
[7]. Allen D M, Lecheheb A 1996 Micro Electo-discharge Machining of Ink Jet Nozzle: Optimum Selection of Material and Machining Parameter. *J. Mater Process Technol* 58 (1): 53-63.
[8]. Masuzawa T, Kuo C L, Fujino M 1994 A combined Electrical Machining Process for Micro Nozzle Fabrication. *Ann CIRP* 43 (1) : 189-192.
[9]. Yu Z Y, Masuzawa T, Fujino M 1998 Micro-EDM for Three-dimensional Cavities-development of Uniform wear method. *Ann CIRP* 47 (1), 169-172.
[10]. Bigot S, Valentincic J, Blatnik O, Junkar M 2006 Micro-EDM parameters optimization *Proceedings of second international conference on multi-material micro manufacture, Grenoble, France* : 20–22.
[11]. Pradhan B B, Bhattacharyya B 2009 Modeling of Micro-EDM during machining of Titanium Alloy, Ti-6Al-4V using RSM and ANN Algorithm. *Proceedings of Institutions of Mechanical Engineers Part B: Journal of Engineering Manufactu*re 223(6): 683-693.
[12]. Somashekhar K. P, Ramachandran N, Mathew J 2010 Optimization of Material Removal Rate in Micro-EDM Using Artificial Neural Network and Genetic Algorithms. *Materials and Manufacturing Processes* 25 (6): 467-475.
[13]. Mustafa A, Ulas C, Ahmet H 2013 Optimization of micro-EDM drilling of inconel 718 superalloy. *Int J of Adv Manuf Tech*. 66 (5-8): 1015-1023.
[14]. Tiwary A P, Pradhan B B, Bhattacharyya B 2014 Application of multi-criteria decision making methods for selection of micro-EDM process parameters *Advances in Manufacturing* 2(3): 251-258.
[15]. Tiwary A P, Pradhan B B, Bhattacharyya B 2013 Parametric Optimization of Micro-EDM Process Using Response Surface Methodology and Principal Component Analysis *Int J of Manuf Tech Res*. 5(3-4): 117-136.
[16]. MacCrimon K R 1968. Decision Making among Multiple Attribute Alternatives: A Survey and Consolidated Approach. Rand memorandum, *RM-4823-ARPA*.
[17]. Triantaphyllou E, Mann S H 1989 An examination of the effectiveness of multi-dimensional decisionmaking methods: a decision-making paradox. *Decision Support Systems* 5(3): 303–312.
[18]. Miller D W, Starr M K 1969 Executive Decisions and Operations Research. Prentice-Hall. *Englewood Cliffs.*
[19]. Zavadskas E K, Antucheviciene J, Šaparauskas J, Turskis Z 2013a Multi-criteria assessment of facades' alternatives: peculiarities of ranking methodology *Procedia Engineering*. 57: 107–112.
[20]. Zavadskas E K, Antucheviciene J, Saparauskas J, Turskis Z 2013b MCDM methods WASPAS and MULTIMOORA: verification of robustness of methods when assessing alternative solutions. *Economic Computation and Economic Cybernetics Studies and Research* 47(2): 5–20.
[21]. Šaparauskas J, Zavadskas E K, Turskis Z 2011 Selection of facade's alternatives of commercial and public buildings based on multiple criteria. *International Journal of Strategic Property Management* 15(2): 189–203.
[22]. Zavadskas E K, Turskis Z, Antucheviciene J, Zakarevicius A 2012 Optimization of weighted aggregated sum product assessment. *Elektronika ir Elektrotechnika – Electronics and Electrical Engineering* 122(6): 3–6.

IOP Conf. Series: Materials Science and Engineering **377** (2018) 012202 doi:10.1088/1757-899X/377/1/012202

[23]. Zolfani S H, Aghdaie M H, Derakhti A, Zavadskas E K, Varzandeh M H M 2013 Decision making on business issues with foresight perspective; an application of new hybrid MCDM model in shopping mall locating. *Expert Systems with Applications* 40(17): 7111–7121.

[24]. D˙ejus T, Antuchevičien˙e J 2013 Assessment of health and safety solutions at a construction site. *Journal of Civil Engineering and Management* 19(5): 728–737

[25]. Stani unas M, Medineckien˙e M, Zavadskas E K, Kalibatas D 2013 To modernize or not: ecological – economical assessment of multi-dwelling houses modernization. *Archives of Civil and Mechanical Engineering* 13(1): 88–98.