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MULTI-RESPONSE OPTIMIZATION OF WEDM PROCESS PARAMETERS USING TAGUCHI BASED DESIRABILITY FUNCTION ANALYSIS

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Abstract
Shape memory alloy has a unique capability to return to its original shape after physical deformation by applying heat or thermo-mechanical or magnetic load. In this experimental investigation, desirability function analysis (DFA), a multi-attribute decision making was utilized to find out the optimum input parameter setting during wire electrical discharge machining (WEDM) of Ni-Ti shape memory alloy. Four critical machining parameters, namely pulse on time (T_{ON}), pulse off time (T_{OFF}), wire feed (WF) and wire tension (WT) were taken as machining inputs for the experiments to optimize three interconnected responses like cutting speed, kerf width, and surface roughness. Input parameter combination T_{ON}= 120 µs., T_{OFF}= 55 µs., WF= 3 m/min. and WT= 8 kg-F were found to produce the optimum results. The optimum process parameters for each desired response were also attained using Taguchi's signal-to-noise ratio. Confirmation test has been done to validate the optimum machining parameter combination which affirmed DFA was a competent approach to select optimum input parameters for the ideal response quality for WEDM of Ni-Ti shape memory alloy.

Keywords: Desirability function analysis; shape memory alloy; Taguchi; WEDM.

1. Introduction

WEDM becomes very popular non-traditional process (NTM) because of its capability to machine complex shapes and geometry and difficult-to-cut conductive material (1). In his thermo-electrical process, WEDM material is removed by a continuous highly focused spark energy developed in between electrode and workpiece (2, 3). Any electrically conductive material irrespective of its hardness can precisely machine using WEDM process. Due to its unique ability, WEDM application dramatically increased in tool and die-making industry, automobile sector, aerospace and nuclear industry where high precise end product is needed.

In this competitive production field, selection of best input parameter setting for desired responses is very difficult due to the presence of variety of choices, contradictory nature of output, etc. To offer this selection process, several distinctive multi-attribute decision making (MADM) procedures are now available (4-11). Among different MADM approach, desirability function analysis (DFA) is very easy to execute as because DFA does not contain complicated mathematical theory or computation (12).

Kanlayasiri et al. (13) used Box–Behnken design based DFA technique to decide an optimum cutting combination for surface roughness (Ra) and dimensional accuracy for WEDM of K460 tool steel. Bhaumik et al (14) used MADM approach GRA coupled with DFA to obtain the optimum level of the input parameters for higher material removal rate and lower tool wear rate (TWR). Gopalakannan et al.

(15) optimized EDM input parameters using DFA approach to maximize MRR and minimize electrode wear rate (EWR) and Ra.
Due to its properties like good biocompatibility, superior fatigue performance, Ni-Ti shape memory alloy is widely used in automotive, biomedical, robotics, aerospace and civil structures etc (16, 17). In this research, MADM approach desirability function analysis has been practiced to elect ideal machining parameter combination for WEDM responses namely average cutting speed, average kerf width and average Ra for Ni-Ti shape memory alloy. Using Taguchi's signal to noise (S/N) ratio, attempts were further made to decide the optimum parameter combination for each input parameter viz. pulse-on time (T_{ON}), pulse-off time (T_{OFF}), wire feed (WF) and wire tension (WT).

2. Experimental setup and Data Collection

A number of experiments was practiced on four axis CNC WEDM (EIPULS 15) following L27 orthogonal array. Different significant machining variables like pulse-on time (T_{ON}), pulse-off time (T_{OFF}), wire feed (WF) and wire tension (WT) were considered (see Table 1) to find out key machinability aspects namely cutting speed (CS), kerf width (KW) and surface roughness (Ra). Brass wire (diameter 0.25 mm) and de-ionized water was used as wire electrode and dielectric medium respectively. From 1.2 mm thickness plate of Ni-Ti shape memory alloy, 5 mm length was cut by each input setting. Using Taylor Hobson 3D profilometer surface roughness or arithmetic mean roughness (Ra) were find out and average value from three measurement were taken as final Ra value. From machine monitor the cutting speed were noted down during each experiment and average value from three measurement were taken for final cutting speed value. The kerf width for each setting were measured using Toolmaker microscope and average value from three measurement were taken as final value.

Table 1. Input variables and their levels

Machining Parameter	**Denotation**	**Unit**	**Level**		
			Low	**Medium**	**High**
Pulse ON Time (T_{ON})	A	μs	110	115	120
Pulse OFF Time (T_{OFF})	B	μs	50	55	60
Wire Feed (WF)	C	m/min	3	5	7
Wire Tension (WT)	D	kg-F	4	6	8

3. Methodology

In this experimental work, a MADM model desirability function analysis has been applied to optimize different correlated responses of WEDM of Ni-Ti shape memory alloy.

3.1 Desirability function analysis

Following steps need to follow for the proposed methodology:
1st Step: Identification of the purposes and its characteristics and decision matrix preparation to represent the performance characteristics with respect to different variables.
2nd Step: Calculation of the desirability index (d_i) value for individual response. d_i value depends on the character of the respective output.

- When output character is "Larger-is-better"

$$d_i = \begin{cases} 0, & x \le x_{min} \\ \left(\dfrac{x - x_{min}}{x_{max} - x_{min}}\right), & x_{min} \le x \le x_{max}, r \ge 0 \\ 1, & x \ge x_{min} \end{cases} \quad (1)$$

here, d_i=Single desirability index;
X_{min} and X_{max} are the lowest and highest values of x;
R= Weight.

- When output character is "smaller-is-better"

$$d_i = \begin{cases} 1, & x \le x_{min} \\ \left(\dfrac{x - x_{max}}{x_{min} - x_{max}}\right), & x_{min} \le x \le x_{max}, r \ge 0 \\ 0, & x \ge x_{max} \end{cases} \quad (2)$$

3rd Step: using the following equation the overall desirability grade (d_G) is evaluated:

$$d_G = \left(d_1^{w_1} * d_2^{w_2} * d_3^{w_3} * .... * d_i^{w_i}\right)^{\frac{1}{w}} \quad (3)$$

here, d_i = Single desirability index;
w_i = weight assigned to individual response respectively;
w = sum of all individual weights.
Highest d_G value is reflected as ideal setting of corresponding input variables.

4. Results and discussions

With varied combination of input parameters Total 27 number of experiments were executed following Taguchi's L_{27} orthogonal array. Different experimental settings and their respective out comes are shown in Table 2.

Table 2. Responses from respective input parameter combination

Run no.	T_{ON} (µs)	T_{OFF} (µs)	Wire Feed (m/min)	Wire Tension (kg-F)	CS (mm/min)	KW (mm)	Ra (µm)
1	110	50	3	4	0.792	0.493	2.870
2	110	55	5	6	0.585	0.491	3.030
3	110	60	7	8	0.425	0.521	3.653
4	115	50	5	8	0.965	0.511	3.925
5	115	55	7	4	0.878	0.498	3.641
6	115	60	3	6	0.876	0.472	3.506
7	120	50	7	6	1.815	0.502	3.014
8	120	55	3	8	1.681	0.492	2.667
9	120	60	5	4	1.215	0.593	3.814
10	110	50	3	4	0.760	0.472	2.730
11	110	55	5	6	0.560	0.502	3.840
12	110	60	7	8	0.496	0.517	3.752
13	115	50	5	8	1.019	0.507	3.879
14	115	55	7	4	0.867	0.472	3.876
15	115	60	3	6	0.870	0.466	3.418
16	120	50	7	6	1.904	0.527	3.017
17	120	55	3	8	1.547	0.498	2.517
18	120	60	5	4	1.187	0.601	3.793
19	110	50	3	4	0.770	0.481	2.806
20	110	55	5	6	0.577	0.52	3.661
21	110	60	7	8	0.408	0.523	3.850
22	115	50	5	8	0.950	0.520	4.015
23	115	55	7	4	0.860	0.458	3.271
24	115	60	3	6	0.896	0.497	3.507
25	120	50	7	6	1.785	0.533	2.867
26	120	55	3	8	1.480	0.481	2.473
27	120	60	5	4	1.079	0.574	3.698

Using desirability function analysis, the optimum combination of the input parameters was determined. From the different correlated responses, "larger-is-better" criteria was executed for average cutting speed whereas "smaller-is-better" criteria were executed for average kerf width (KW) and average surface roughness (Ra). The desirability index (d_i) for average cutting speed was calculated using Eq. 1 and on the contrary the same for average kerf width and Ra were calculated using Eq. 2. The weightage for each responses were taken as 33%. After calculating the d_i value for each respective responses, the overall desirability grade (d_G) was calculated using Eq. 3. The distinct desirability index and overall desirability grade for individual responses are shown in Table 3. In DFA, highest value of d_G signifies the optimum combination. From the Table 3, it is clearly understandable that run no. 26 has the highest d_G value with 0.84548. DFA gives the optimum input parameter setting which is T_{ON}: 120 µs., T_{OFF}: 55 µs., WF: 3 m/min. and WT: 8 kg-F.

Table 3. Optimization using DFA

Run no.	Individual Desirability index (d_i)			d_G	Rank
	CS	KW	Ra		
1	0.25668	0.75525	0.74254	0.52748	10
2	0.11832	0.76923	0.63878	0.39108	14
3	0.01136	0.55944	0.23476	0.11678	24
4	0.37233	0.62937	0.05837	0.24259	20
5	0.31417	0.72028	0.24254	0.38372	15
6	0.31283	0.90210	0.33009	0.45692	12
7	0.94051	0.69231	0.64916	0.75263	4
8	0.85094	0.76224	0.87419	0.82925	2
9	0.53944	0.05594	0.13035	0.16080	23
10	0.23529	0.90210	0.83333	0.56459	7
11	0.10160	0.69231	0.11349	0.20310	21
12	0.05882	0.58741	0.17056	0.18375	22
13	0.40842	0.65734	0.08820	0.29076	17
14	0.30682	0.90210	0.09014	0.29582	16
15	0.30882	0.94406	0.38716	0.48681	11
16	1	0.51748	0.647211	0.69700	5
17	0.76136	0.72028	0.97147	0.81237	3
18	0.52072	0	0.14397	0	25
19	0.24198	0.83916	0.78405	0.54532	8
20	0.11297	0.56643	0.22957	0.24838	19
21	0	0.54546	0.10700	0	25
22	0.36230	0.56643	0	0	25
23	0.30214	1	0.48249	0.52969	9
24	0.32620	0.72727	0.32944	0.43120	13
25	0.92046	0.47552	0.74449	0.69072	6
26	*0.71658*	*0.83916*	*1*	*0.84548*	*1*
27	0.44853	0.18881	0.20558	0.26270	18

After finding the overall optimum input parameter setting, attempts were further made to get the optimum parameter setting for single quality characteristic using Taguchi's signal to noise (S/N) ratio (18). Taguchi's main effect plot of S/N ratio for higher cutting speed, smaller kerf width and Ra with respect to WEDM input parameters viz. T_{ON}, T_{OFF}, WF and WT are shown in Figures. 1-3. For higher cutting speed, parameter combination T_{ON}= 120 µs., T_{OFF}= 50 µs., WF= 3 m/min. and WT= 6 kg-F was found to yield the preferred outcomes (Figure 1). On the other hand, the parameter setting T_{ON}= 115 µs., T_{OFF}= 55 µs., WF= 3 m/min. and WT= 6 kg-F was found optimum for smaller kerf width (Figure 2). In the same way, for the smaller Ra, by using Taguchi's S/N ratio, the optimum input parameter combination was found as T_{ON}= 120 µs., T_{OFF}= 55 µs., WF= 3 m/min. and WT= 6 kg-F (Figure 3). It is obvious from the figures that specific responses has its individual specific parameter setting.

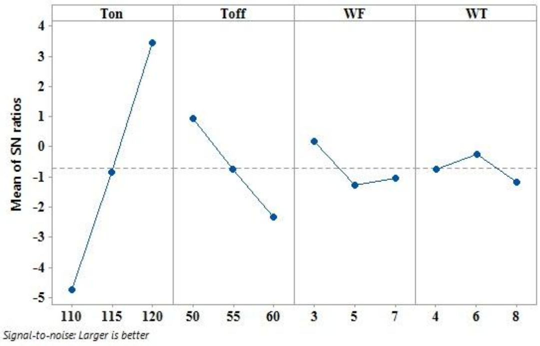

Figure 1. Main effects plot for S/N ratio for cutting speed.

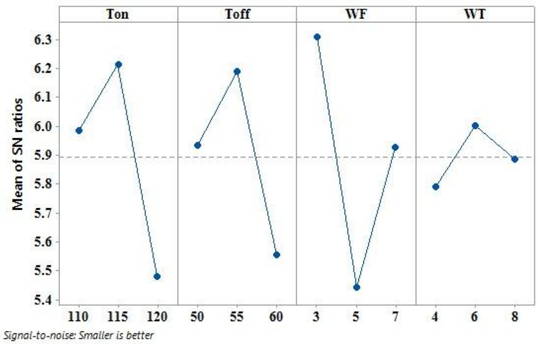

Figure 2. Main effects plot for S/N ratio for kerf width.

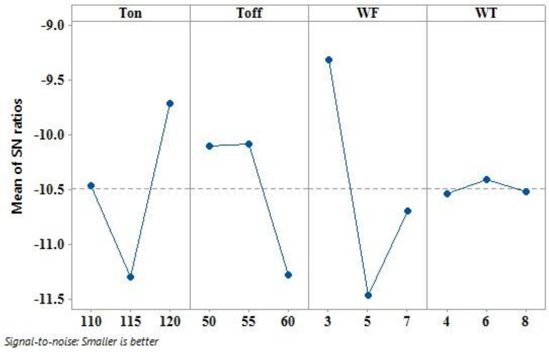

Figure 3. Main effects plot for S/N ratio for Ra.

4.1 Confirmation test

Table 7 indicates that, among 27 experiments, experiment no. 26 has the highest overall desirability grade (d_G) which specifies that the input parameter combination of A3-B2-C1-D3 has the optimum multiple performance characteristic. According to the optimum parameter combination, confirmation test was conducted to figure out the quality characteristics for WEDM of Ni-Ti shape memory alloy (see Table 4). Confirmation test shows improvement in the quality of WEDM responses.

Table 4. Confirmation test.

	Taguchi-DFA	**Confirmation test**
Optimum combination	A3-B2-C1-D3	A3-B2-C1-D3
Average cutting speed	1.48	1.52
Average kerf width	0.481	0.397
Average surface roughness	2.473	2.464

5. Conclusion

According to Taguchi's L_{27} orthogonal array, Ni-Ti shape memory alloy was machined by WEDM process. Experimental results were optimized using a desirability function analysis technique. From the investigation results, the following conclusions might be drawn:

a) Desirability function analysis comprises a lesser amount of mathematical calculations and very easy to execute compare to other optimization strategies. Consequently, DFA will be useful for the engineers who does not have very strong statistical background.
b) Experiment no. 26 has the highest overall desirability grade (d_G) which specifies that the input parameter setting of T_{ON}= 120 µs., T_{OFF}= 55 µs., WF= 3 m/min. and WT= 8 kg-F has the optimum multiple performance characteristic.
c) Optimum process parameters for each preferred responses were determined by the Taguchi S/N ratio.
d) Parameter combination of T_{ON}= 120 µs., T_{OFF}= 50 µs., WF= 3 m/min. and WT= 6 kg-F was optimum for higher cutting speed. Whereas process parameter setting T_{ON}= 115 µs., T_{OFF}= 55 µs., WF= 3 m/min. and WT= 6 kg-F was optimum for smaller kerf width. T_{ON}= 120 µs., T_{OFF}= 55 µs., WF= 3 m/min. and WT= 6 kg-F was found optimum for smaller Ra.

The accuracy of the proposed optimization technique is limited to the studied environment and parameter range. It can be improved by conducting more experiments with varying range of machining parameter and machining environment. DFA can also be employed as a future work for other WEDM responses like corner deviation, MRR, etc. with high accuracy.

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