Optimization in Wire Electric Discharge Machining of Nickel-Titanium Shape Memory Alloy

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Abstract. The present study focuses on optimizing the process parameters during machining of NiTi (Nickel-Titanium) shape memory alloy by wire electric discharge machining (Wire EDM) for simultaneously maximizing material removal rate and minimizing tool wear rate using brass wire as electrode. Taguchi’s design with utility and modified utility optimization techniques have been used for simultaneous multi-response optimization. Different analyses were performed to determine the optimal settings in both utility and modified utility concepts. The optimal results of both methods disclose that the pulse on time of 115µsec and pulse off time of 40µsec with spark gap set voltage of 20V are useful for maximizing material removal rate and minimizing tool wear rate. The optimization results indicate that the spark gap set voltage is the majority significant parameter that affects the tool wear rate and material removal rate.

Keywords: Nickel-Titanium; shape memory alloy; Taguchi optimization; Utility and Modified utility; Material removal rate; Tool wear rate.

1. Introduction
In current years Nickel Titanium (NiTi) shape memory alloys (SMAs) have gained importance in both engineering as well as biomedical applications because of their superelastic and shape memory effects. Nickel Titanium SMAs are characterized by superior mechanical properties like high ductility and superior corrosion [1]. From last few decades Nickel Titanium SMAs are being used in various biomedical applications due to its shape memory effects.

Slowly the usage of these smart materials in various biomedical applications is being increasing day by day due to its superelastic (Pseudo-elastic) nature [2]. The medical grade NiTi pseudo-elastic alloys are employed in biomedical applications such as bone plate, mandible fracture plates, dentistry, cardio-vascular stents etc [3, 4, 5]. The traditional machining of these NiTi smart materials is very complicated due to the pseudo-elastic nature of the alloy. Therefore many non-traditional machining processes like laser machining, electric discharge machining, water jet machining and wire electric discharge machining (Wire EDM) are employed for machining of NiTi SMAs [6,7]. Wire EDM is most preferred non-conventional machining process for NiTi SMAs as it exhibits exceptional capability during the machining. Wire EDM plays a significant role in the metal cutting industries and is used to produce complicated and intricate shapes. Wire EDM is extensively applicable in making press tools, dies, and machining of micro products with high accuracy with good surface quality. As NiTi superelastic alloy is a costly material and wire EDM process is both time consuming and costly process, the optimization of process variables of Wire EDM for machining of NiTi pseudo-elastic alloy for obtaining higher material removal rate (MRR), better surface finish (SR) and lesser tool wear

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rate (TWR) is very much essential [8]. It has been found that there is no single optimal level of machining variables, as the influences of these variables on output responses are quite different, thus multi-performance optimization is performed [9].

\[ \eta = \text{Multi-Response S/N ratio} \]
\[ \eta_{MRR} = \text{S/N ratio for material removal rate} \]
\[ \eta_{TWR} = \text{S/N ratio for tool wear rate} \]

Very few researchers have carried out the work to analyse the wire EDM performance characteristics for different compositions of NiTi SMAs. Pulse on time (T\text{ON}), pulse off time (T\text{OFF}), wire feed (WF), Servo-voltage, spark gap set voltage (SV) etc are the major input parameters of wire EDM varied and studied against the output performances such as MRR and SR [10, 11]. Neeraj Sharma et al. (2015) have studied the parameter optimization on Wire EDM of porous Ni\text{40}Ti\text{60} alloy. Multi-response optimization has been carried out and the variables obtained are T\text{ON} = 124 \mu\text{s}, T\text{OFF} = 25 \mu\text{s} and SV = 30V [11]. Majority of the work in machining of NiTi SMA using wire EDM is carried out in the area of modelling and machinability aspects, but very few researchers have worked on optimization of wire EDM for machining NiTi SMA and pseudo-elastic alloy. Manjaiah et al. (2014) tried to optimize the Wire EDM input parameters for higher MRR and better surface finish of TiNiCu ternary SMA. The optimum settings were found to be (T\text{OFF} = 48\mu\text{s}, SV = 36.16V and T\text{ON} = 130\mu\text{s}). Utility concept simultaneous optimization method was applied to optimize MRR and SR [12]. Taguchi method was applied for optimization of EDM process parameters by Daneshmand et al.(2014) for NiTi shape memory alloy and studied the impact of pulse on time, pulse off time, pulse current and gap voltage on output responses such as surface roughness and material removal rate [13]. Similarly other researchers have investigated optimization of wire EDM process parameters using different optimization techniques such as Taguchi optimization techniques for multi-response optimization. The literature survey reveals that the optimization of machining variables on responses like MRR and TWR of NiTi pseudo-elastic alloy using Wire EDM machining process with brass wire as electrode has not been completely explored. The study also reveals that researchers have conducted very partial work on optimization of Wire EDM process variables using utility concept and modified utility method for NiTi shape memory alloy and no such work is available for pseudo-elastic alloy. Therefore paper focuses on optimization of multi performance characteristics of NiTi shape memory alloy using utility and modified utility concept, as there is a need to generate optimal sets of process variables satisfying performance characteristics such as MRR and TWR. Further an effort has been made to optimize the T\text{ON}, T\text{OFF}, and SV in Wire EDM of NiTi shape memory alloy with brass wire as electrode.

2. Methodology & Material

2.1. Taguchi method

Most appropriate method for finding the optimal settings of control variables is Taguchi method, which helps in making process insensitive to noise factors [14]. Taguchi’s method with utility concept and modified utility optimization techniques are used to solve multi performance characteristics problem to calculate and analyse the effects of process parameters on performance measures. Further analysis of variance (ANOVA) and analysis of means (ANOM) are used for investigation of multiple performance characteristics.

2.2. Work material

For the present experimental study NiTi shape memory alloy is used as work material. These NiTi SMAs are broadly used in medical implants such as mandible fracture, orthopedic and orthodontic
applications. Work material has been purchased from Hong Kong Hanz Material Technology Co., Ltd, China. NiTi SMA plate of 100 mm x 180 mm x 2 mm dimensions is considered as work material for performing the experiments. The NiTi pseudo-elastic alloy has two major constituents, Ni (55.74%) and Ti (44.13%). The NiTi SMA alloy has the tensile strength of 825 MPa and yield strength of 202 MPa.

3. Experimental Procedure

3.1. Wire EDM tool material and experimental design plan

The machining operations and related experimentations were carried out on Ecocut Elpuls-15 CNC Wire EDM machine. Circle of 10 mm diameter is used as the cutting profile to be machined on NiTi plate. A brass wire with 0.25 mm diameter is used as electrode material for machining of NiTi SMA material. The machined NiTi SMA plate mounted on fixtures in Wire EDM is shown in figure 1. In present experimental study three input process parameters are considered for machining of NiTi SMA alloy, namely T\text{ON}, T\text{OFF} and SV. The three different process parameters and their three different levels are presented in Table 1. The information about the fixed process parameters of wire EDM are presented in Table 2. Design plan of experimentation was performed by using L\textsubscript{9} orthogonal array as shown in Table 3.

![Figure 1. NiTi shape memory alloy plate used in machining](image)

| Factor | Parameter | Symbol | Level 1 | Level 2 | Level 3 |
|--------|-----------|--------|---------|---------|---------|
| A      | Pulse on Time (µsec) | T\text{ON} | 105     | 115     | 125     |
| B      | Pulse off Time (µsec) | T\text{OFF} | 25      | 40      | 55      |
| C      | Spark Gap Set Voltage (Volts) | SV | 20      | 40      | 60      |

| Sl. No. | Parameter       | Value               |
|---------|-----------------|---------------------|
| 1       | Work material   | NiTi SMA            |
| 2       | Wire Electrode  | Brass of 0.25 mm Diameter |
| 3       | Peak Current    | 12 A                |
| 4       | Dielectric fluid| De-ionized Water    |
| 5       | Servo Feed      | 2150 mm/min         |
| 6       | Pulse Peak Voltage | 11 V               |
| 7       | Wire Feed       | 6 m/min             |
### Experimental design plan as per standard L9 orthogonal array

| Trial No | TON (µsec) | TOFF (µsec) | SV (V) | TON (µsec) | TOFF (µsec) | SV (V) |
|----------|------------|-------------|--------|------------|-------------|--------|
| A        | B          | C           | A      | B          | C           | A      |
| 1        | 1          | 1           | 1      | 105        | 25          | 20     |
| 2        | 1          | 2           | 2      | 105        | 40          | 40     |
| 3        | 1          | 3           | 3      | 105        | 55          | 60     |
| 4        | 2          | 1           | 3      | 115        | 25          | 60     |
| 5        | 2          | 2           | 1      | 115        | 40          | 20     |
| 6        | 2          | 3           | 2      | 115        | 55          | 40     |
| 7        | 3          | 1           | 2      | 125        | 25          | 40     |
| 8        | 3          | 2           | 3      | 125        | 40          | 60     |
| 9        | 3          | 3           | 1      | 125        | 55          | 20     |

3.2. Experimental performance characteristics
In the current experimental examination, the performance characteristics considered are MRR and TWR.

3.3. Measurement of performance measures

3.3.1. Material Removal Rate (MRR). A digital stop watch has been used for measuring the machining time. The Kerf width or Width of cut is measured by using Faro gage co-ordinate measuring machine (CMM), in which 3 mm probe is used to measure outer diameter ($D_o$), inner diameter ($D_i$) and height or thickness ($h$) of the machined components. The machined NiTi plate fixed on vice to measure all the values in CMM is shown in figure 2. Equation 1 shows the formula used for calculating MRR.

$$MRR = V \times b \times h \text{ mm}^3/\text{min.}$$

Where,
- $V_c = \text{Cutting Speed (mm/min)}$
- $b = \text{Width of cut or Kerf width (mm)}$
- $h = \text{Height (Thickness) of Material (mm)}$

**Figure 2. Measurement in FARO GAUGE CMM**
3.3.2. Tool Wear Rate (TWR). TWR is the chief factor because it influences dimensional accuracy and the shape to be produced. Tool wear rate is the plodding failure of machining tools because of regular operation. TWR is expressed in grams/min. The wire after machining for each trial is collected and weighed. In the present study 20 m length of the wire is weighed before and after machining. TWR for the Wire EDM operation can be calculated by using equation 2.

\[
TWR = \frac{((W_i - W_f) \times WF)}{20} \text{ grams/min.}
\]  

(2)

Where,
- \(W_i\) = Weight of electrode before machining (grams/m)
- \(W_f\) = Weight of electrode after machining (grams/m)
- WF = Wire feed rate (m/min)

4. Results and Discussions

Computed values of MRR and TWR are presented in Table 4.

Table 4. Experimental Results

| Expt. No. | TON (µsec) | TOFF (µsec) | SV (V) | TON (µsec) | TOFF (µsec) | SV (V) | MRR (mm³/min) | TWR (grams/min) |
|-----------|------------|-------------|--------|------------|-------------|--------|---------------|----------------|
| 1         | 1          | 1           | 1      | 105        | 25          | 20     | 0.8940        | 0.05178        |
| 2         | 1          | 2           | 2      | 105        | 40          | 40     | 1.5484        | 0.07206        |
| 3         | 1          | 3           | 3      | 105        | 55          | 60     | 0.3083        | 0.07098        |
| 4         | 2          | 1           | 3      | 115        | 25          | 60     | 2.6134        | 0.10242        |
| 5         | 2          | 2           | 1      | 115        | 40          | 20     | 1.9242        | 0.10374        |
| 6         | 2          | 3           | 2      | 115        | 55          | 40     | 2.2657        | 0.05274        |
| 7         | 3          | 1           | 2      | 125        | 25          | 40     | 2.5288        | 0.15318        |
| 8         | 3          | 3           | 1      | 125        | 40          | 60     | 2.2757        | 0.05886        |
| 9         | 3          | 3           | 1      | 125        | 55          | 20     | 2.2867        | 0.10530        |

4.1. Utility concept

In utility concept, the S/N ratio for given response is calculated, in which MRR and TWR are determined separately. For the present work MRR has to be maximized and TWR has to be minimized. The formulae used for S/N ratio are as follows.

\[
\eta_{MRR} = -10\log_{10}\left[\frac{1}{N}\sum \frac{1}{\text{MRR}^2}\right]
\]

(3)

\[
\eta_{TWR} = -10\log_{10}\left[\frac{1}{N}\sum \text{TWR}^2\right]
\]

(4)

\[
\eta = (W_1 \times \eta_{MRR}) + (W_2 \times \eta_{TWR})
\]

(5)

Where, \(w_1\) and \(w_2\) = weighting factors, decided based on priorities [15]. These weighting factors are related with S/N ratio of the responses. In current study the value of \(w_1\) and \(w_2\) are taken as 0.5. The S/N ratio based on utility concept is listed in Table 5.

ANOM was utilized to resolve the best possible levels of variables and the outcomes are presented in Table 6. The most favorable mixture of process variables for concurrently optimizing MRR and TWR is A2, B2 and C1. Hence a combination of 115µsec TON, 40µsec TOFF and 20V spark gap set voltage is valuable for simultaneously maximizing MRR and minimizing TWR. Optimal parameter setting obtained using utility concept is shown in Figure 3.
Table 5. S/N Ratio based on utility concept

| Expt. No | Individual S/N Ratio | $\eta_{\text{MRR}}$ (dB) | $\eta_{\text{TWR}}$ (dB) | $\eta$ (dB) |
|----------|-----------------------|---------------------------|-------------------------|-------------|
| 1        | -0.9732               | 25.7168                   | 12.3718                 |             |
| 2        | 3.7977                | 22.8461                   | 13.3219                 |             |
| 3        | -10.2205              | 22.9773                   | 6.3784                  |             |
| 4        | 8.3441                | 19.7923                   | 14.0682                 |             |
| 5        | 5.6850                | 19.6811                   | 12.6830                 |             |
| 6        | 7.1040                | 25.5572                   | 16.3306                 |             |
| 7        | 8.0583                | 16.2960                   | 12.1771                 |             |
| 8        | 7.1423                | 24.6036                   | 15.8729                 |             |
| 9        | 7.1842                | 19.5514                   | 13.3678                 |             |

Table 6. ANOM summary based on S/N ratio for utility concept

| Factor   | Level 1 | Level 2 | Level 3 | Optimum Level | Value |
|----------|---------|---------|---------|---------------|-------|
| TON (µsec) | 10.6907 | 14.3606 | 13.8060 | 2             | 115   |
| TOFF (µsec) | 12.8724 | 13.9593 | 12.0256 | 2             | 40    |
| SV (V) | 14.8584 | 13.5860 | 10.4128 | 1             | 20    |

Figure 3. Optimal settings of parameters obtained in utility concept

Table 7 lists the summary of ANOVA (Analysis of variance) results based on utility concept for NiTi SMA. From figure 4 and table 7 it is observed that factor ‘C’ i.e. spark gap set voltage has the highest contributing factor (47.85%) followed by factor ‘A’ i.e. pulse on time (35.73%). However factor ‘B’ i.e. pulse off time (8.58%) have the slightest influence in optimizing the multi-performance characteristics in Wire EDM for SMA.
Table 7. ANOVA results for utility concept

| Factor | Degree of freedom | Sum of square | Mean square | % Contribution |
|--------|------------------|---------------|-------------|----------------|
| A      | 2                | 23.4812       | 11.7406     | 35.73          |
| B      | 2                | 5.6376        | 2.8188      | 8.58           |
| C      | 2                | 31.4512       | 15.7256     | 47.85          |
| Error  | 2                | 5.1547        | 2.5773      | 7.84           |
| Total  | 8                | 65.7247       | 8.2156      | 100            |

Figure 4. Percentage contribution of parameters

4.2. Modified utility concept

The S/N ratio for the responses, MRR and TWR are listed below

\[ \eta_{MRR} = -10 \log_{10} \left( \frac{1}{N} \sum \frac{1}{MRR^2} \right) \]  

(6)

\[ \eta_{TWR} = -10 \log_{10} \left( \frac{1}{N} \sum [TWR]^2 \right) \]  

(7)

In this method, the multi-response S/N ratio is defined as,

\[ \eta = (W_1 \times \eta_{MRR}) + (W_2 \times \eta_{TWR}) \]  

(8)

Where \( w_1 \) and \( w_2 \) = weighting factors.

In the present investigation the value of \( w_1 \) and \( w_2 \) is taken as 0.5. The present concept initiates a new-fangled change to the utility technique [16]. The new change take up weighting factors directly to the responses to obtain the multi-response objective function (\( Ob_{mr} \)) and is given as

\[ Ob_{mr} = (W_1 \times MRR) + (W_2 \times TWR) \]  

(9)
Thus, the S/N ratio related with each trial is,

$$\eta = -10 \log_{10} \{ (W_1 \times MRR) + (W_2 \times TWR) \}^2 \] \quad (10)$$

The calculated value of multi-response S/N ratio for each experiment is illustrated in Table 8. Based on modified utility concept the ANOM outcomes are listed in Table 9. From Figure 5 and Table 9 the optimal combination of process variables for concurrently optimizing material removal rate and tool wear rate is 2-2-1 i.e. A2, B2 and C1. Hence a combination of 115µsec T_{ON}, 40µsec T_{OFF} and 20V spark gap set voltage is useful for simultaneously maximizing MRR and minimizing TWR.

Table 8. S/N Ratio based on modified utility concept

| Expt. No | Individual S/N Ratio | η_{MRR} (dB) | η_{TWR} (dB) | η (dB) |
|----------|----------------------|--------------|--------------|--------|
| 1        | -0.9732              | 25.7168      | 24.7435      |
| 2        | 3.7977               | 22.8461      | 26.6438      |
| 3        | -10.2205             | 22.9773      | 12.7568      |
| 4        | 8.3441               | 19.7923      | 28.1364      |
| 5        | 5.6850               | 19.6811      | 25.3661      |
| 6        | 7.1040               | 25.5572      | 32.6612      |
| 7        | 8.0583               | 16.2960      | 24.3542      |
| 8        | 7.1423               | 24.6036      | 31.7459      |
| 9        | 7.1842               | 19.5514      | 26.7356      |

Table 9. ANOM summary based on modified utility concept

| Factor     | Level 1 | Level 2 | Level 3 | Optimum level | Value |
|------------|---------|---------|---------|---------------|-------|
| TON (µsec) | 21.3813 | 28.712 | 27.1179 | 2             | 115   |
| TOFF (µsec)| 25.7447 | 27.916 | 24.0512 | 2             | 40    |
| SV (V)     | 29.7169 | 27.611 | 20.8257 | 1             | 20    |

The ANOVA results using modified utility concept for NiTi SMA is tabulated in Table 10. From Figure 4 and Table 10 it can be observed that spark gap set voltage is the most contributing factor (47.85%) followed by pulse on time (35.73%). However pulse off time (8.58%) has the least effects in optimizing the material removal rate and tool wear rate.

Table 10. ANOVA table for modified utility concept

| Factor | Degree of freedom | Sum of square | Mean square | % Contribution |
|--------|------------------|--------------|-------------|----------------|
| A      | 2                | 93.9248      | 46.9624     | 35.73          |
| B      | 2                | 22.5503      | 11.2752     | 8.58           |
| C      | 2                | 125.8049     | 62.9024     | 47.85          |
| Error  | 2                | 20.6187      | 10.3093     | 7.84           |
| Total  | 8                | 262.8987     | 32.8623     | 100            |
4.3. Validating experiments
The validating experiments were carried out at the optimal settings of process parameter i.e A2, B2 and C1. For the confirmation experiment MRR and TWR are found to be 2.6381 $\text{mm}^3/\text{min}$ and 0.0498 grams/min respectively.

The observed S/N ratio values were calculated by using the formulae of each multi-performance characteristics optimization methods. The validating experiments results are presented in Table 11. It can be observed that the prediction error is well within 95% confidence interval and therefore adequacy of the model is justified.

| Method               | Predicted S/N Ratio | Observed S/N Ratio | Predicted Error | Inference     |
|----------------------|---------------------|--------------------|-----------------|---------------|
| Utility Concept      | 17.2735             | 17.2424            | 0.0018          | Less than 0.05|
| Modified Utility Concept | 34.5470             | 34.4847            | 0.0018          | Less than 0.05|

5. Conclusion
In the current experimental study, the output parameters such as MRR and TWR were analyzed in Wire EDM of NiTi SMA using brass wire as electrode. Taguchi’s method along with utility and modified utility techniques were used to optimize the process parameters in which the $T_{\text{ON}}$, $T_{\text{OFF}}$ and SV are the identified process input parameters for simultaneously decreasing the TWR and increasing the MRR. Optimum combination for the minimum TWR and maximum MRR are achieved by using S/N ratio. The SV is found to be the most significant parameter followed by $T_{\text{ON}}$ and $T_{\text{OFF}}$ on optimizing the multiple performances. The optimal parameter settings obtained from both multi-response optimization methods are 2-2-1 for Factor ‘A’ i.e. $T_{\text{ON}}$ is level 2 and for Factor ‘B’ i.e. $T_{\text{OFF}}$ is level 2 and for Factor ‘C’ i.e. SV is level 1. Therefore the results of both utility and modified utility methods are found to same during the optimization process. Further the researchers can use other optimization techniques like quality loss function, artificial neural networks and compare the results with utility and modified utility methods of optimization.
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