Investigations on Wire Electro Discharge Machining (WEDM) characteristics of NiTi Shape Memory Alloy

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Abstract. NiTi(Nickel Titanium) Shape Memory Alloys (SMA) are expeditiously replacing conventional materials in aerospace, automobile, robotics and bio-engineering fields due to its distinctive characteristics like shape memory effect, pseudo elasticity and biocompatibility. Machining of these alloys is strenuous by traditional methods. The unconventional methods like wire electro discharge machining (WEDM) can competently machine these SMAs. But improper selection of WEDM parameters may lead to undesirable results such as poor surface finish and higher machining time. The present study attempts to explore the influence of three system variables; pulse on time, pulse off time and wire feed on performance criteria's like material removal rate (MRR) and surface roughness (SR) during WEDM of NiTi SMA. Experiments were conducted in accordance with Full Factorial Design (FFD) and results were analysed using Response surface methodology (RSM) based mathematical models. The investigation outcomes revealed that pulse on time has more influence on MRR and SR than pulse off time and wire feed. Maximum MRR is achieved at higher pulse on time with the combination of higher pulse off time and lower wire feed rate. Better surface finish is observed at decreased pulse on time, increased pulse off time and minimum wire feed rate.

Keywords: Wire EDM; Machining, Material Removal Rate; Surface Roughness; Shape Memory Alloy.

1. Introduction
Nickel-Titanium (NiTi) alloys are the advanced engineering materials which are now rapidly replacing conventional materials because of its outstanding characteristics like Shape Memory Effect, Pseudo Elasticity, wear, fatigue resistance and non-corrosive property [1-3]. Because of these unique properties NiTi alloy has find its need in wide variety of fields such as aerospace, Micro Electro Mechanical Systems, automotive, Robotic applications. NiTi Shape Memory Alloys (SMA) have excellent biocompatibility as compared to other shape memory alloys [5]. NiTi SMAs unique anti-magnetic properties and magnetic resonance imaging compatibility [6], along with its excellent biocompatibility, made it as a favourite choice of material for biomedical applications such as surgical equipments, implants and stents etc. But on the other side of the coin, due to NiTi alloys high mechanical properties and pseudo elasticity property poses difficulty in traditional machining of these alloys [4]. Therefore non-traditional machining methods like Laser Beam Machining, Electro Discharge Machining, Wire EDM, Electro Chemical Machining and Water Jet Machining etc. can be employed which can machine hard materials and complex profiles very swiftly with high accuracy and better surface finish.

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WEDM process melts and vaporizes material from the work surface by using continues sparks between work surface and wire electrode in a dielectric medium [7]. WEDM is extensively preferred in the manufacturing of dies, fixtures, gauges and biomedical parts such as implants and stents [7]. The system parameters of WEDM machines such as Pulse on time ($T_{on}$), Pulse off time ($T_{off}$), Wire Feed rate (WF), SV (Servo Voltage), Peak Current, Wire Tension, Dielectric pressure, table feed etc. have effect on performance criterions such as Tool Wear Rate (TWR), MRR, SR, surface morphology and surface topography. Improper selection of these system parameters may cause undesirable results such as poor surface finish, high cost of machining, tool breakage etc. Many authors have carried out extensive research to analyze the WEDM performance characteristics.

Chen et al. (2007) reported that during WEDM of NiTiZr and NiTiCr ternary SMAs, the increase in discharge current and pulse duration maximises MRR and SR [8]. Sabouni, H.R et al. (2012) used Taguchi’s technique with L$_{18}$ orthogonal array (OA) to find optimal system variables for WEDM of NiTi alloy, according to the author increase in voltage causes reduction of MRR and TWR [9]. Ali Alidoosti et al. (2013) in their research used full factorial design to investigate WEDM characteristics of NiTi alloy and concluded that MRR increases with discharge energy [10]. Saeed Daneshmand et al. (2013) used L$_{18}$ OA for analysis purpose. Author’s analysis uncovered that pulse on duration and servo voltage have positive impact on MRR whereas reduction in tool wear is observed for grater pulse on time and increases discharge current [11]. Manjaiah et al. (2015) found that increase in pulse on duration, table feed and peak current maximises MRR and SR whereas reduces marginally with pulse off duration [12]. Vaibhav Gaikwad et al. (2016) conducted experiments using Taguchis L$_{36}$ OA during WEDM of cryo-treated NiTi SMA, at the end author inferred that conductivity of work material, discharge current and pulse on duration are the influencing factors which affect MRR [13]. Manjaiah et al. (2016) investigated MRR and sub-surface characteristics in Wire EDM of TiNiCu SMA. During analysis author observed that pulse on duration and servo voltage are strong influencers of MRR and SR [14].

It is evident from the past research that, several authors have investigated the impact of WEDM system variables on performance criterions of various SMAs. But there are no reports or investigations found on performance characteristic studies on WEDM of medical grade NiTi SMA. The current study attempts to explore the machinability of NiTi SMA which focuses on the study of effect of WEDM system variables on responses. RSM based mathematical models are utilized to analyse the influence of Wire EDM system variables namely $T_{on}$, $T_{off}$ and WF over the responses like SR and MRR.

2. Experimental Details

2.1. Work and Tool material
The NiTi shape memory alloy of 100 mm X 180 mm X 2 mm rectangular plate is used as work material in present study. This NiTi shape memory material is composed of 55.74% Nickel and 44.13% Titanium by atomic percentage weight. It has tensile strength of 825 MPa and yield strength of 202 MPa with austenite finish temperature of 35$^{+10}$C. The work material is imported from Republic of China. Zinc (Zn) coated brass wire of 0.25 mm diameter is used as wire electrode tool material in WEDM machine.

2.2. Design of Experiments and Methodology
Experiments were planned and conducted as per FFD using Taguchi’s L$_{27}$ orthogonal array. Response surface methodology based mathematical models are used for the present analysis. RSM is an extensively used statistical tool to analyse the effect of process parameters on response criteria [15]. By using this method second order regression model can be developed which can be used to check adequacy of test model. RSM model provides sufficient information regarding main effects and interaction effects of system variables on performance measures.
2.3. Process Parameters

The current investigations are focused towards analysis of effects of system variables on performance characteristics during Wire EDM of NiTi shape memory alloy. Wire EDM machine provides vast number of system parameters to choose from which can be varied over a wide range. Improper selection of system parameters while machining may result into poor surface finish, more machining time, uneconomical machining and wire electrode breakage while machining. Therefore the present study attempts to explore the influence of three system variables. The system parameters for present investigation were selected based on through pilot study and proper literature survey. The three input system parameters considered for experimentations are $T_{on}$, $T_{off}$ and $WF$ at three different levels. Table 1 depicts the selected system parameters and their levels where as fixed system parameters are tabulated in Table 2.

Table 1. Selected system Parameters and levels.

| Code | Parameter            | Symbol | Level 1 | Level 2 | Level 3 |
|------|----------------------|--------|---------|---------|---------|
| A    | Pulse on time (µsec) | $T_{on}$ | 105     | 115     | 125     |
| B    | Pulse off time (µsec)| $T_{off}$ | 25      | 40      | 55      |
| C    | Wire Feed (m/min)    | $WF$   | 4       | 6       | 8       |

Table 2. Fixed System Parameters.

| S.No | Parameters         | Values                  |
|------|--------------------|-------------------------|
| 1    | Work Material      | Medical Grade NiTi Alloy|
| 2    | Thickness          | 2mm                     |
| 3    | Wire electrode     | Zinc coated brass wire of 0.25 mm |
| 4    | Peak current       | 12A                     |
| 5    | Dielectric fluid   | De-ionised water        |
| 6    | Servo Feed         | 2150 mm/min             |
| 7    | Pulse peak voltage | 11V                     |
|      | Servo Voltage      | 20V                     |

2.4. Experimentation

The experiments were performed on computer numerically controlled Electronica Ecocut Elpuls-15 wire electro discharge machine. This machine provides good flexibility to operator while choosing parameter values over a wide range. 0.25 mm diameter brass wire with zinc coating is employed as wire electrode tool material for machining. De-mineralised water as dielectric medium is used while machining of medical grade NiTi SMA. For the reduction of external noise during machining air conditioned atmosphere is maintained throughout. The NiTi plate is held rigidly against work table using fixture. The experimental setup and cutting profile of machined surface is shown in figure 1. A circular profile of 10 mm diameter is used as cutting profile. The machined profile of NiTi SMA is further used for performance measurements.

2.5. Monitoring of output responses

To calculate $Material\ Removal\ Rate$, the total machining time required to cut the desired profile is recorded, the cut width is measured using coordinate measuring machine. Then MRR is calculated with the help of equation 1.

$$MRR = V_c \times b \times h \quad \text{mm}^3/\text{min}.$$  \hspace{1cm} (1)

Where,
\[ V_c = \text{Cutting Speed} = \pi D/T_m \text{ in mm/min.} \]
\[ T_m = \text{Machining Time in min} \]
\[ D = \text{Diameter in mm} \]
\[ b = \text{Kerf width (Width of cut) in mm} \]
\[ h = \text{Plate thickness in mm} \]

Surface roughness (SR) of the machined surface is measured with the help of Carl Zeiss SURFCOM 1500SD2 surface roughness tester instrument. The instrument with setup is shown in figure 2. Average surface roughness value (R_a) in microns is measured and values are recorded for further analysis.

Figure 1. WEDM experimental setup.

Figure 2. Carl Zeiss SURFCOM 1500SD2 surface roughness tester.

3. Response Surface Modelling

A second order regression model is developed using Response Surface Methodology for performance variables MRR and SR. While modelling \( T_{on}, T_{off} \) and WF were considered as input system parameters. The general regression model for three variables is given by equation (2)

\[ y = a_0 + a_1 T_{on} + a_2 T_{off} + a_3 W^2 + a_4 T_{on}^2 + a_5 T_{off}^2 + a_6 W T_{on} + a_7 T_{off} W + a_8 T_{on} W + a_9 T_{off} + a_{10} T_{on}^2 + a_{11} W^2 + a_{12} T_{off}^2 + a_{13} W T_{off} + a_{14} W T_{on}^2 + a_{15} W T_{off}^2 \]  

Where \( y \) is Response i.e. MRR or SR and \( a_0, a_1, ..., a_{23} \) are regression coefficients of the model.

The developed mathematical models used to predict MRR and SR are depicted in equation (3) and (4) respectively.

\[ MRR \,(\text{mm}^3/\text{min}) = -96.7 + 1.68 T_{on} + 0.0352 T_{off} - 0.155 W F - 0.00687 T_{on}^2 - 0.00940 T_{off}^2 + 0.0524 W^2 - 0.00722 T_{off} W - 0.00334 T_{on} W - 0.000094 W T_{off} W \]  

(3)

\[ SR, R_a \, (\mu m) = 4.8 - 0.141 T_{on} + 0.255 T_{off} - 1.95 W F + 0.00079 T_{on}^2 - 0.00104 T_{off}^2 - 0.0134 W^2 - 0.00128 T_{on} W - 0.0220 T_{off} W - 0.00732 T_{on}^2 W \]  

(4)
The adequacy of the developed model is checked by performing the analysis of variance (ANOVA) for the regression model. The significance level considered at 5% (0.05) or 95% of confidence level. The ANOVA for MRR is tabulated in Table 3 and for SR in Table 4.

### Table 3. ANOVA for MRR (mm³/min).

| Source        | Degrees of Freedom | Sequential Sum of Square | Adjusted Sum of Square | Adjusted Mean Square | F       | P       |
|---------------|--------------------|--------------------------|------------------------|---------------------|---------|---------|
| Regression    | 9                  | 8.9124                   | 8.91237                | 0.99026             | 8.44    | 0.000   |
| Residual Error| 17                 | 1.9935                   | 1.99347                | 0.11726             |         |         |
| Total         | 26                 | 10.9058                  |                        |                     |         |         |

R² = 81.7%  R²-adjusted = 72.0%

### Table 4. ANOVA for SR, Ra (µm).

| Source        | Degrees of Freedom | Sequential Sum of Square | Adjusted Sum of Square | Adjusted Mean Square | F       | P       |
|---------------|--------------------|--------------------------|------------------------|---------------------|---------|---------|
| Regression    | 9                  | 33.1923                  | 33.1923                | 3.68804             | 13.16   | 0.000   |
| Residual Error| 17                 | 4.7641                   | 4.7641                 | 0.28024             |         |         |
| Total         | 26                 | 37.9565                  |                        |                     |         |         |

R² = 87.4%  R²-adjusted = 80.8%

From the regression ANOVA it is learnt that the developed model for MRR and SR are significant at 95% confidence level as P value is within the required significance level. Also the adequacy of model can be checked using coefficient of determinants (R²). The R² values for MRR and SR are 81.7% and 87.4% respectively. Hence the proposed models can be used to predict the performance criterion values during machining of NiTi SMA by WEDM process.

### 4. Results and Discussion

The plan of experiments in uncoded values and measured experimental performance data for MRR and SR for wire EDM of NiTi SMA are summarised in Table 5.

#### 4.1. Main effects plot

Influence of process parameters at different levels over the mean of response of data can be analysed by plotting main effect graphs [15].

Figure 3 shows the influence of system variables (T\textsubscript{on}, T\textsubscript{off} and WF) on material removal rate. It is found from the figure 3 that material removal rate increases sharply when pulse on duration increases from 105 to 115µsec and then it slightly diminishes after that. This is due to spark discharge energy is maximised with increase in pulse on duration which accelerates melting and evaporation of work material there by increasing the MRR. Further increment in T\textsubscript{on} beyond 115µsec MRR drops slightly. It may be due to re-solidification of material over the machined area, however this effect is low. Also increase in pulse off time maximises machining time required there by increasing MRR. The reason may be due to proper flushing of eroded material from the machined area, And sufficient T\textsubscript{off} duration exposes fresh surface for melting and evaporation which results in higher MRR. Increase in WF decreases MRR because higher WF reduces the contact duration of electrode wire with the work materials there by lowering intensity of sparks produced.

It is noticed from the figure 4 that increment in T\textsubscript{on} duration results in poor surface finish. This may be due to increase in T\textsubscript{on} duration maximises the spark intensity which may cause deeper and larger craters. Whereas increase in T\textsubscript{off} duration results in lesser sparks generation which may cause formation of shallow craters. This establishes effective flushing which reduces the surface roughness. The increase in WF provides fresh wire electrode for spark generation at faster rate which produces...
impulsive sparks. Therefore higher roughness is observed when wire feed is increased from 4-8 m/min.

Table 5. Full Factorial Design in uncoded values and experimental results for MRR and SR.

| EXP NO | T-on (µsec) | T-off (µsec) | WF (m/min) | MRR (mm³/min) | SR, Ra (µm) |
|--------|-------------|--------------|------------|---------------|-------------|
| 1      | 105         | 25           | 4          | 2.326         | 1.4758      |
| 2      | 105         | 25           | 6          | 1.908         | 1.6822      |
| 3      | 105         | 25           | 8          | 2.438         | 2.0375      |
| 4      | 105         | 40           | 4          | 2.401         | 1.8501      |
| 5      | 105         | 40           | 6          | 2.184         | 1.6924      |
| 6      | 105         | 40           | 8          | 2.484         | 1.5745      |
| 7      | 105         | 55           | 4          | 2.560         | 1.8507      |
| 8      | 105         | 55           | 6          | 2.200         | 1.5759      |
| 9      | 105         | 55           | 8          | 2.298         | 1.5021      |
| 10     | 115         | 25           | 4          | 3.081         | 2.7911      |
| 11     | 115         | 25           | 6          | 3.197         | 3.8731      |
| 12     | 115         | 25           | 8          | 3.485         | 2.8114      |
| 13     | 115         | 40           | 4          | 3.327         | 2.5862      |
| 14     | 115         | 40           | 6          | 2.982         | 3.4262      |
| 15     | 115         | 40           | 8          | 3.109         | 2.6956      |
| 16     | 115         | 55           | 4          | 4.597         | 2.6725      |
| 17     | 115         | 55           | 6          | 3.914         | 2.5181      |
| 18     | 115         | 55           | 8          | 3.973         | 2.1402      |
| 19     | 125         | 25           | 4          | 3.701         | 3.9130      |
| 20     | 125         | 25           | 6          | 3.393         | 3.4720      |
| 21     | 125         | 25           | 8          | 3.552         | 5.7250      |
| 22     | 125         | 40           | 4          | 3.713         | 3.0838      |
| 23     | 125         | 40           | 6          | 3.179         | 4.6240      |
| 24     | 125         | 40           | 8          | 2.896         | 5.8562      |
| 25     | 125         | 55           | 4          | 3.153         | 3.2273      |
| 26     | 125         | 55           | 6          | 3.328         | 3.4485      |
| 27     | 125         | 55           | 8          | 3.252         | 3.8662      |

Figure 3. Main Effects plot for MRR.

Figure 4. Main Effects Plot for SR.
4.2. Analysis of interaction effects of process parameters

4.2.1. MRR Analysis. The two dimensional interaction plots were drawn by utilizing the regression model developed for the responses MRR and SR. The process variables T\textsubscript{on}, T\textsubscript{off} and WF were considered at intermediate levels within the scope of low to high level. The two factor interaction effect plots were developed by keeping one parameter on hold at middle level and considering other two parameters for analysis.

Figure 5 depicts the combined effects of pulse on and pulse off on response material removal rate where WF is held at its middle level (6 m/min). There exists nonlinear relationship for all the values of T\textsubscript{on} and T\textsubscript{off} on MRR. The response MRR increases as T\textsubscript{on} and T\textsubscript{off} increases, maximum MRR is noticed at T\textsubscript{on} at 115 µsec and T\textsubscript{off} 55 µsec. It may be because of the reason that the discharge energy increased with increase in T\textsubscript{on} duration which produces intensive sparks which in turn melts and evaporates the NiTi alloy at faster rate. The longer pulse off duration helps in sweeping away the eroded material by dielectric fluid which exposes the fresh surface for discharge machining.

Figure 5. Influence of T\textsubscript{on} and T\textsubscript{off} on MRR.

Figure 6. Influence of T\textsubscript{on} and WF on MRR.

Figure 7. Influence of T\textsubscript{off} and WF on MRR.

T\textsubscript{on} and WF interaction withhold value of T\textsubscript{off} 40 µsec on MRR is depicted in figure 6. The relative increase in MRR is noticed with increase in T\textsubscript{on} and reduces for higher WF. And the higher MRR is recorded for T\textsubscript{on}=115 µsec and WF= 4 m/min. It may be due to the reason that lower feed rate of tool
material provides sufficient time for generating intensive sparks on work material. Figure 7 indicates effects of $T_{\text{off}}$ and WF on MRR at $T_{\text{on}}$ hold value of 115 µsec. MRR is maximum for higher $T_{\text{off}}$ (55 µsec) and lower WF (4m/min). An increase in MRR is possible because of greater discharge energy which erodes the work-material and clears the debris along the machined surface using dielectric fluid at longer pulse off duration and providing the large spark gap for the explosion.

4.2.2. Analysis of SR: The effect of $T_{\text{on}}$ and $T_{\text{off}}$ for a hold value of WF at 6 m/min is shown in figure 8. It is found from the figure 8 that good surface finish is obtained for lower $T_{\text{on}}$ duration at all the values of $T_{\text{off}}$ and SR increases almost linearly with increase in $T_{\text{on}}$ from 105-125 µsec. Desired values of SR is noticed at lower $T_{\text{on}}$(105 µsec) and higher $T_{\text{off}}$(55 µsec). The reason for this may be due to formation of wider and shallow-crater because of low intensity of sparks.

![Figure 8](image1.png)
**Figure 8.** Influence of $T_{\text{on}}$ and $T_{\text{off}}$ on SR.

![Figure 9](image2.png)
**Figure 9.** Influence of $T_{\text{on}}$ and WF on SR.

![Figure 10](image3.png)
**Figure 10.** Influence of $T_{\text{off}}$ and WF on SR.

Figure 9 depicts the effect of interaction of $T_{\text{on}}$ duration and WF rate on SR for the withhold value of $T_{\text{off}}$-40 µsec. It is clear from the figure-9 that lower SR is obtained for lower $T_{\text{on}}$ duration and for all the values of WF within the range. But when $T_{\text{on}}$ is increased beyond 110 µsec SR increases slowly and reaches maximum at 125µsec when WF is at 8m/min. The higher discharge energy at higher level of $T_{\text{on}}$ is responsible for higher surface roughness by creating larger and deeper craters. Figure-10 depicts the combined effect of $T_{\text{off}}$ and WF rate on SR for the hold value of pulse on time at 115 µsec. It is evident from the graph that SR shows nonlinear behaviour for this interaction. It is noticed from the graph that good surface finish is obtained for higher pulse off time i.e. at 55 µsec and lower feed rate. At a combination of higher pulse-off duration and reduced feed rate at fixed value of $T_{\text{on}}$, rate of
spark produced is less also higher pulse off duration helps in flushing out debris effectively from the machined surface thereby giving good surface finish.

5. Conclusions
The present study focused on exploration of influence of input process parameters $T_{on}$, $T_{off}$ and WF on performance characteristics during WEDM of medical grade NiTi SMA. The MRR and SR are selected performance criteria for the analysis. Experiments were planned using FFD and results were analysed based on RSM based quadratic models.

It can be concluded that MRR and SR are majorly influenced by pulse on duration whereas wire feed and pulse-off duration have moderate effect on response. Increased material removal rate is noticed with increase in $T_{on}$ and $T_{off}$ but decreases for higher WF. But at the same time poor surface finish is observed at higher $T_{on}$, lower $T_{off}$ and WF. Also $T_{on}$ and WF have grater interaction effect on MRR. The effect of MRR is predominant for higher $T_{on}$ duration and lower WF rate. Surface finish is profoundly influenced by the combined effect of $T_{on}$ and $T_{off}$ duration when wire feed is held at mid-level. The increment in $T_{on}$ duration and reduction in $T_{off}$ duration increases surface roughness.

It is witnessed that maximum MRR is found at the combination of $T_{on}=120$ µsec and $T_{off}=55$ µsec and WF= 4 m/min. And desirable surface finish is noticed at $T_{on}=105$ µsec, $T_{off}=55$ µsec and WF= 4 m/min. It is imperative to have trade off among system parameters to obtain maximum MRR and minimum SR. Further research can be extended to optimise selected process parameters to maximise material removal rate and to improve surface finish simultaneously.

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