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# Analysis of Process Parameters in Wire EDM with NITINOL Shape Memory Alloy using Multi Objective Grey Relational Grade

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## *Abstract*

*The position of traditional machining process are taken by non-traditional machining processes because of increasing demands of high surface finish and machining of complex shape geometries,. Wire EDM is one of the non-traditional machining processes. Surface roughness and material removal rate are of most importance in the field of machining processes. This paper gives brief description of the Grey relational theory and Taguchi optimization technique, in order to optimize the cutting parameters in Wire EDM for NITINOL shape memory alloy. The objective of optimization is to attain the minimum surface roughness and the best surface quality along with that higher material removal rate. In this present study NITINOL shape memory alloy is used as a work piece, brass wire of 0.25mm* *diameter used as a tool, orthogonal array has been used. The input parameters selected for optimization Peak current, pulse on time, pulse off time, wire feed, and wire tension,also other parameter are kept constant. For each experiment material removal rate and surface roughness was determined. With the help of multi objective optimization technique grey relational theory, the optimal value is obtained for material removal rate and surface roughness and by using Taguchi optimization technique. Additionally, the analysis of variance (ANOVA) is used for identifying the most affecting parameter factor.*

***Keywords**: WEDM, Material Removal Rate, Surface Roughness,Micro Hardness. Grey Relational Theory, Taguchi, Analysis of Variance (ANOVA)*

## INTRODUCTION

In the last decade, smart structural or intelligent materials have great interest due to their potential scientific and technological importance. A material which has built-in or intrinsic sensor, actuator, and control mechanism whereby it is capable of sensing an external stimuli, such as electric or magnetic fields, pH, stress, moisture, temperature, responding to it in a predictable or controllable manner, in an appropriate time and reverting to its original state as soon as the stimuli are removed is known as “smart material”. There are Varieties of smart materials already exist in nature and being researched extensively. These included materials are SMAs, piezoelectric materials, magnetostrictive materials, electrostrictive materials and pH-sensitive polymers. Each individual type of smart material has exhibits the one or more properties such as temperature, shape, stiffness, viscosity, and volume that can be significantly altered. Due to their unique ability to respond to stimuli, they are being used in various applications in the field of sensors and actuators. Among them, SMAs have been widely used as smart and functional materials because of their unique properties of high damping capacity, high energy to weight proportion, shape memory impact (SME), great compound resistance, pseudoelasticity (superelasticity) and biocompatibility. Nickel-Titanium (NiTi) is the most widely used and commercially available SMA for both passive and active applications due to its superior mechanical and shape-memory properties [1].

The unique shape memory behavior was firstly observed in Au-Cd alloy by Chang and Read in1951, while pseudoelasticity had been seen in this alloy by Olan-der in 1932. In the early 1960s, Buehler and co-workers discovered the shape memory effect in an equiatomic alloy of nickel and titanium (NiTi) named as Nitinol, which is considered a breakthrough for engineering applications of shape memory materials. The expression "NITINOL" was authored from its sythesis and its place of disclosure: (Nickel-Titanium-Naval Ordnance Laboratory). Till date the Nitinol has been the amalgam indicating unrivaled shape memory attributes among all SMAs. NiTi can display in two distinctive temperature-subordinate precious stone structures (stages) called martensite (lower temperature) and austenite (higher temperature or guardian stage). Subsequently, Nitinol is presently generally utilized as a part of biomedical gadgets, for example, curve wires and guide wires,endovascular stents, dental files, vena cava filters etc. [2].

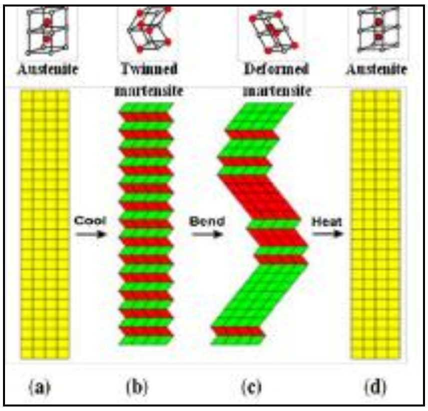


***Fig1:** Phase Transformation*

The stage change in the middle of the austenite stage and the martensite period of SMAs is delegated a first-arrange stage change. Austenite to martensite stage changes in SMAs are additionally dispersion less and reversible. Because of its capacity in experiencing reversible first-arrange stage change, SMAs comprises fascinating practices, for example, superelasticity or pseudoelasticity by change, and the shape-memory impact [3].

## EXPERIMENTAL PROCEDURE:

### Materials And Methods

Material employed in this study was NITINOL Shape Memory Alloy. It is an alloy of Ni and Ti and well known for high hardness and toughness. As received NITINOL bar has length 500 mm and diameter 4 mm respectively. Each specimen was wire-EDMed along its length into 5mm shown in Figure 2.

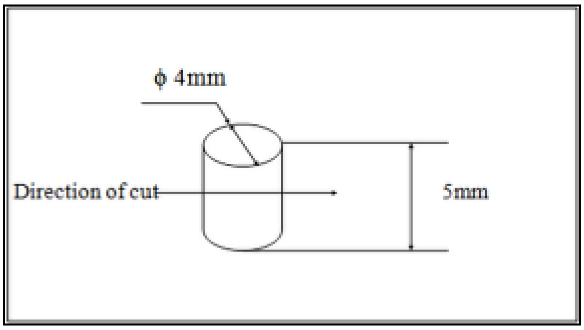


***Fig 2:**Sample preparation*

The wire-EDM machine used in this study was ELEKTRA SUPERCUT 734SERIES 2000 with the wire electrode made from brass. The wire was 0.25mm in diameter and the wire is kept in tension using a mechanical tensioning device reducing the tendency of producing inaccurate parts [4] .At the experimentation before sample was fixed to machine the initial weight of the sample is measured with the help of weight measurement instrument.Then the sample was fixed with the table of machine and precaution was kept that the sample remaining perpendicular to the cutting wire as shown in Figure 1. Then machine run as per given program and input parameters are given to machine and other parameters are kept constant. After machining, the specimen was collected and the weight of sample was measured with the help of weighing machine then recorded the weight and time required to cut the sample which is helpful to calculating the material removal rate. Similarly 27 trialswere done and sample was numbered as per the trial number. The surface roughness of the EDMed surface along the cutting direction was taken and note down the readings. The surface finish parameter employed to indicate the surface quality in this experiment was the arithmetic mean roughness (Ra). The surftest has a resolution varying from 0.01 µm to 0.4 µm depending on the measurement range. The Cut off length is 0.25, Evaluation length is 1.75and Stylus speed is 0.25mm/sec etc. Figure 3 shows experimental set up.

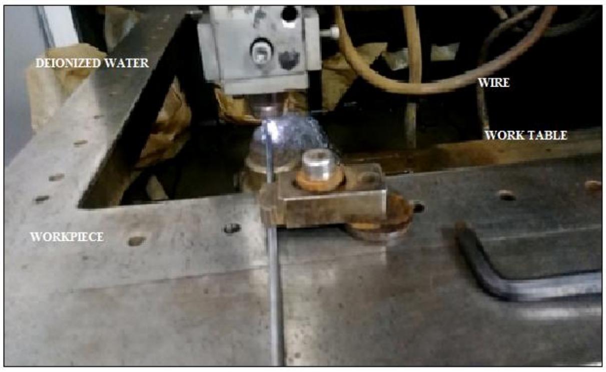


***Fig3:** Experimental set up*

## EXPERIMENTAL DESIGN:

The analysis performed in this study was a screening test. In this test, there were five controlled variables examined including Peak current (IP), Pulse-on time (Ton), Pulse-off time (Toff), Wire bolster (WF) and wire pressure (WT). Three levels of every variable were chosen appeared in Table 1. The base number of trials is discovering by taking after recipe.

$$\text{Minimum number of trial} = F^{(l-1)}$$

$$\text{Minimum number of trial} = 5^{(3-1)} = 5^2$$

$$\text{Minimum number of trial} = 25 \text{ trials}$$

Where, F is the input factors, l is the number of levels

So, for more accurate results L27 array will be selected.

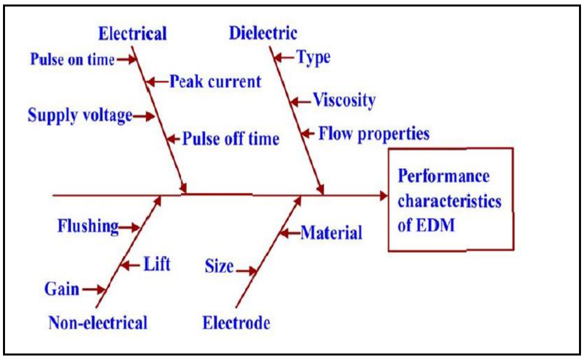


***Fig 4:*** *Ishikawa cause and effect diagram for EDM*

***Table 1:*** *Experimental levels*

| **Control factor** | **Level 1** | **Level 2** | **Level 3** | **Unit** |
|---|---|---|---|---|
| Peak current | 30 | 60 | 90 | Ampere |
| Pulse on time | 110 | 120 | 130 | Machine unit |
| Pulse off time | 40 | 50 | 60 | Machine unit |
| Wire feed | 4 | 8 | 12 | m / min |
| Wire tension | 4 | 8 | 12 | Kg-f |

## TAGUCHI OPTIMIZATION METHOD:

Taguchi design of experiment is a powerful analysis tool for modeling and analyzing the influence of control factors on performance output [5] .Optimization of process parameters is the key step in the Taguchi method to achieve high quality without increasing cost. However, originally Taguchi method was designed to optimize single performance characteristics. According to Taguchi method, the S/N ratio is the ratio of Signal to Noise, where signal represents the desirable value and noise represents the undesirable value. Which is used to calculate the Signal to Noise Ratio (S/N) using the Eq.1. The experimental results are now transformed into a signal-to-noise (S/N) ratio. Lower amount of surface roughness show the high productivity of Wire EDM. Therefore, Smaller the Better are applied to calculate the S/N ratio of surface roughness respectively [6]. So, Smaller the Better characteristic is used for S/N ratio calculation. The optimal setting would be the one which could achieve lowest S/N ratio. The S/N Ratio for the experiments conducted is shown in Table 2

Higher machine feed rate gives higher value of MRR and vice versa. Theoretically, material erosion is influenced by the spark energy. As feed rate increase, MRR also increases till it reaches optimum [7]. Material removal process in WEDM is the result of spark erosion by transformation of electrical energy to thermal energy as the wire electrode is fed through the workpiece. Larger amount of Material removal rate show the high productivity of Wire EDM. Therefore, Higher the Better are applied to calculate the S/N ratio of Material removal rate respectively. So, Higher the Better characteristic is used for S/N ratio calculation. The S/N Ratio for the experiments conducted is shown in Table 3

It was found that the machining parameters, for example, the beat on/off term, crest present, open circuit voltage, servo reference voltage, electrical capacitance and table pace are the basic parameters for the estimation of the material evacuation rate (MRR) and surface unpleasantness (Ra) . For the ideal choice of procedure parameters, the Taguchi strategy has been widely utilized as a part of assembling keeping in mind the end goal to enhance forms with single execution attributes [8].

In the Taguchi analysis, the raw data than be transformed into S/N ratio values. The criteria for the surface roughness is "Smaller the Better" while for the material removal rate is "Higher the Better" which can be expressed as below [8, 10].

$S/N_{LB} = -10\log(\Sigma yi)$ (1)

Where, $S/N_{LB}$ is Signal to noise ratio, $y_i$ is output characteristic (Surface Roughness (Ra)

$S/NHB = -10\log(\Sigma 1/yi)$ (2)

Where, $S/N_{HB}$ is Signal to noise ratio, $y_i$is output characteristic (Material Removal Rate (MRR))

**Signal To Noise Ratio Calculation For Surface Roughness:**

$S/N_{LB} = -10\log(\Sigma {y_i}^2)$

$\therefore S/N_{LB} = -10\log(3.65^2)$

$\therefore S/N_{LB} = -11.2459$

***Table 2:****Signal to noise ratio calculation for Surface Roughness*

| SR.NO. | IP | Ton | Toff | WF | WT | Surface Roughness | S/N Ratio |
|---|---|---|---|---|---|---|---|
| 1 | 30 | 110 | 40 | 4 | 4 | 3.65 | -11.24586 |
| 2 | 30 | 110 | 40 | 4 | 8 | 2.55 | -8.13080 |
| 3 | 30 | 110 | 40 | 4 | 12 | 2.70 | -8.62728 |
| 4 | 30 | 120 | 50 | 8 | 4 | 2.10 | -6.44439 |
| 5 | 30 | 120 | 50 | 8 | 8 | 2.60 | -8.29947 |
| 6 | 30 | 120 | 50 | 8 | 12 | 3.10 | -9.82723 |
| 7 | 30 | 130 | 60 | 12 | 4 | 1.60 | -4.08240 |
| 8 | 30 | 130 | 60 | 12 | 8 | 0.70 | 3.09804 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 9 | 30 | 130 | 60 | 12 | 12 | 1.98 | -5.93330 |
| 10 | 60 | 110 | 50 | 12 | 4 | 3.75 | -11.48063 |
| 11 | 60 | 110 | 50 | 12 | 8 | 2.50 | -7.95880 |
| 12 | 60 | 110 | 50 | 12 | 12 | 3.76 | -11.50376 |
| 13 | 60 | 120 | 60 | 4 | 4 | 2.66 | -8.49763 |
| 14 | 60 | 120 | 60 | 4 | 8 | 1.91 | -5.62067 |
| 15 | 60 | 120 | 60 | 4 | 12 | 2.88 | -9.18785 |
| 16 | 60 | 130 | 40 | 8 | 4 | 3.96 | -11.95390 |
| 17 | 60 | 130 | 40 | 8 | 8 | 3.52 | -10.93085 |
| 18 | 60 | 130 | 40 | 8 | 12 | 3.88 | -11.77663 |
| 19 | 90 | 110 | 60 | 8 | 4 | 3.78 | -11.54984 |
| 20 | 90 | 110 | 60 | 8 | 8 | 3.16 | -9.99374 |
| 21 | 90 | 110 | 60 | 8 | 12 | 2.68 | -8.56270 |
| 22 | 90 | 120 | 40 | 12 | 4 | 2.92 | -9.30766 |
| 23 | 90 | 120 | 40 | 12 | 8 | 1.65 | -4.34968 |
| 24 | 90 | 120 | 40 | 12 | 12 | 2.83 | -9.03573 |
| 25 | 90 | 130 | 50 | 4 | 4 | 3.12 | -9.88309 |
| 26 | 90 | 130 | 50 | 4 | 8 | 2.60 | -8.29947 |
| 27 | 90 | 130 | 50 | 4 | 12 | 3.10 | -9.82723 |

## Signal to noise ratio calculation for material removal rate:

$S/N_{HB} = -10\log(\Sigma \frac{1}{{y_i}^2})$

$\therefore S/N_{HB} = -10\log(\frac{1}{7.5^2})$

$\therefore S/N_{HB} = 17.5012$

*Table 3:Signal to noise ratio calculation for material removal rate*

| SR.NO. | IP | Ton | Toff | WF | WT | MRR | S/N Ratio |
|---|---|---|---|---|---|---|---|
| 1 | 30 | 110 | 40 | 4 | 4 | 7.5 | 17.50123 |
| 2 | 30 | 110 | 40 | 4 | 8 | 15.3 | 23.68623 |
| 3 | 30 | 110 | 40 | 4 | 12 | 8.2 | 18.23728 |
| 4 | 30 | 120 | 50 | 8 | 4 | 31.6 | 29.98795 |
| 5 | 30 | 120 | 50 | 8 | 8 | 36.4 | 31.21335 |
| 6 | 30 | 120 | 50 | 8 | 12 | 6.0 | 15.56303 |
| 7 | 30 | 130 | 60 | 12 | 4 | 11.7 | 21.35504 |
| 8 | 30 | 130 | 60 | 12 | 8 | 3.8 | 11.53508 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 9 | 30 | 130 | 60 | 12 | 12 | 6.2 | 15.79779 |
| 10 | 60 | 110 | 50 | 12 | 4 | 18.8 | 25.46003 |
| 11 | 60 | 110 | 50 | 12 | 8 | 26.4 | 28.42340 |
| 12 | 60 | 110 | 50 | 12 | 12 | 25.5 | 28.14167 |
| 13 | 60 | 120 | 60 | 4 | 4 | 15.4 | 23.74173 |
| 14 | 60 | 120 | 60 | 4 | 8 | 7.3 | 17.28675 |
| 15 | 60 | 120 | 60 | 4 | 12 | 38.5 | 31.70053 |
| 16 | 60 | 130 | 40 | 8 | 4 | 12.9 | 22.21397 |
| 17 | 60 | 130 | 40 | 8 | 8 | 5.9 | 15.47660 |
| 18 | 60 | 130 | 40 | 8 | 12 | 17.8 | 25.01902 |
| 19 | 90 | 110 | 60 | 8 | 4 | 25.8 | 28.23457 |
| 20 | 90 | 110 | 60 | 8 | 8 | 9.8 | 19.85643 |
| 21 | 90 | 110 | 60 | 8 | 12 | 25.0 | 27.95880 |
| 22 | 90 | 120 | 40 | 12 | 4 | 15.0 | 23.52183 |
| 23 | 90 | 120 | 40 | 12 | 8 | 5.0 | 13.97940 |
| 24 | 90 | 120 | 40 | 12 | 12 | 15.0 | 23.52183 |
| 25 | 90 | 130 | 50 | 4 | 4 | 36.2 | 31.17583 |
| 26 | 90 | 130 | 50 | 4 | 8 | 5.0 | 13.90732 |
| 27 | 90 | 130 | 50 | 4 | 12 | 20.0 | 26.02060 |

## ANALYSIS OF VARIANCE

Relative impact of every element is controlled by examination of difference strategy (ANOVA) and results are introduced in Table 4 and 5. ANOVA comes about demonstrate that surface unpleasantness and MRR generally influenced by which parameters. It is important to say that certainty level of 95% is utilized for analysispurpose, so p-esteem under 0.05 will build up the hugeness of element.

***Table 4**: Analysis of Variance for SR, using Adjusted SS for Tests*

| **Source** | **DO F** | **Seq. SS** | **Adj. SS** | **Adj. M S** | **F- value** | **P- value** |
|---|---|---|---|---|---|---|
| IP | 2 | 3.4802 | 3.4802 | 1.7401 | 9.87 | 0.002 |
| Ton | 2 | 2.0154 | 2.0154 | 1.0077 | 5.72 | 0.013 |
| Toff | 2 | 2.5465 | 2.5465 | 1.2732 | 7.23 | 0.006 |
| WF | 2 | 2.7930 | 2.7930 | 1.3965 | 7.92 | 0.004 |
| WT | 2 | 2.7199 | 2.7199 | 1.3600 | 7.27 | 0.005 |
| Error | 16 | 2.8195 | 2.8195 | 0.1762 | - | - |
| Total | 26 | 16.3745 | | | | |

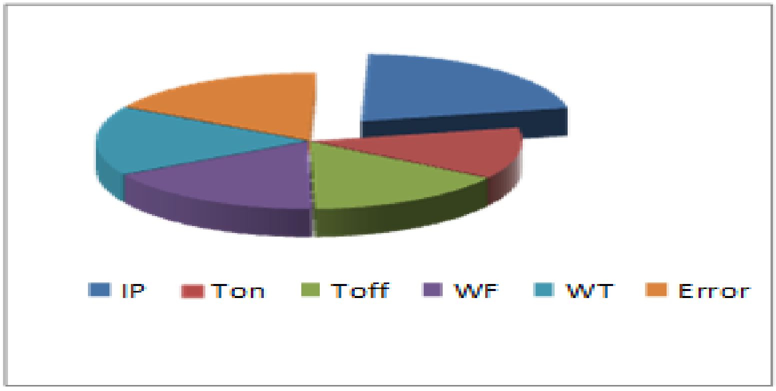


***Fig 5****: % Contribution of factors for surface roughness*

Where, DOF= Degree of Freedom, Seq. SS =Seq. Sum of Square, Adj. SS = Adj. Sum of Square, Adj. M S= Adj. Mean of Square

***Table 5:****Analysis of Variance for MRR, using Adjusted SS for Tests*

| Source | DO F | Seq. SS | Adj. SS | Adj. M S | F- value | P- value |
|---|---|---|---|---|---|---|
| IP | 2 | 104.3 | 104.3 | 52.1 | 0.48 | 0.626 |
| Ton | 2 | 165.1 | 165.1 | 82.6 | 0.76 | 0.482 |
| Toff | 2 | 599.7 | 599.7 | 299.8 | 2.78 | 0.092 |
| WF | 2 | 108.6 | 108.6 | 54.3 | 0.50 | 0.614 |
| WT | 2 | 222.0 | 222.0 | 111.0 | 1.03 | 0.380 |
| Error | 16 | 1727.0 | 1727.0 | 107.9 | - | - |
| Total | 26 | 2926.6 | | | | |

Where, DOF= Degree of Freedom, Seq. SS =Seq. Sum of Square, Adj. SS = Adj. Sum of Square, Adj. M S= Adj. Mean of Square

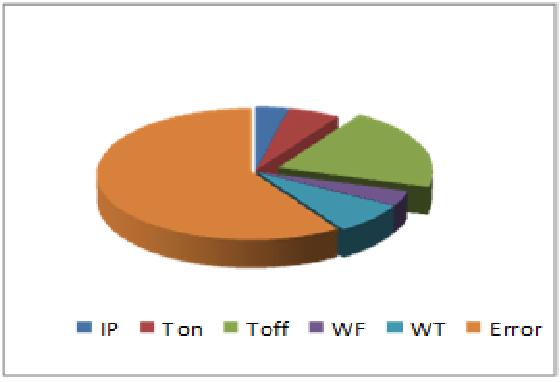


***Fig 6:****% Contribution of factors for material removal rate*

## MULTI RESPONSE PARAMETRIC OPTIMIZATION

In many cases process parameters cannot be set only for one response, as the objective would be minimizing some response and maximize some response simultaneously. Hence there is need for a multi objective optimization.

## Gray Relation Analysis

The Gray social investigation is a technique for measuring the level of guess among the groupings utilizing a Gray social evaluation. It is another strategy for performing forecast, social examination, and basic leadership in numerous areas[9]. Be that as it may, conventional Taguchi technique can't unravel multi-target streamlining. Along these lines, the Taguchi strategy combined with Gray social investigation can help this issue. Dark Relational Analysis (GRA) is a standardization assessment strategy to tackle a more entangled multi-execution attributes enhancement successfully.

## Determination Of Normalized S/N Ratio &Deviation Sequence

Normalize means the measured values of parameters can be varied with the ranging from zero to one. This process is known as Grey relational normalization [10].

The absolute difference between the reference sequence $x_0^i(k)$and the comparability sequence $x_0^*(k)$after normalization is known as the deviation sequence$\Delta_{0i}k$. It is determined using Eq. (3, 4). Values are represented in Table 6 [11].

## Normalized S/N Ratio for Surface Roughness

By using the Eq.3 the normalize S/N Ratio for Surface Roughness is calculated as follows.

$$x_i^*(k) = \frac{max\, x_i^o(k) - x_i^o(k)}{max\, x_i^o(k) - min\, x_i^o(k)} \text{............ (Eq.3)}$$

$$\therefore x_i^*(k) = \frac{3.0980 - (-11.24586)}{3.0980 - (-11.95390)}$$

$$\therefore x_i^*(k) = 0.9530$$

## Deviation Sequence for Surface Roughness

By using the Eq.4 Deviation Sequence for Surface Roughness is calculated as follows.

$$\Delta_{oi}k = |x_o^i(k) - x_o^*(k)| \text{............ (Eq.4)}$$

$$\Delta_{oi}k = 1 - x_i^*(k)$$

$$\therefore \Delta_{oi}k = 1 - 0.952960$$

$$\therefore \Delta_{oi}k = 0.0470$$

## Normalized S/N Ratio for MRR

By using the Eq.5 the normalize S/N Ratio for Material Removal Rate is calculated as follows.

$$x_i^*(k) = \frac{x_i^o(k) - min\, x_i^o(k)}{max\, x_i^o(k) - min\, x_i^o(k)} \text{............ (Eq.5)}$$

$$\therefore x_i^*(k) = \frac{17.50123 - 31.701}{31.0701 - 11.535}$$

$$\therefore x_i^*(k) = 0.2959$$

## Deviation Sequence for MRR

By using the Eq.6the Deviation Sequence for Material Removal Rate is calculated as follows.

$\Delta_{oi}k = |x_o^*(k) - x_i^*(k)|$………… (Eq.6)

$\Delta_{oi}k = 1 - x_i^*(k)$

$\therefore \Delta_{oi}k = 1 - 0.2959$

$\therefore \Delta_{oi}k$=0.7041

***Table 6:*** *Normalized S/N ratio &Deviation Sequence for Surface Roughness*

| Sr.No. | **Surface Roughness** | | **Material Removal Rate** | |
|---|---|---|---|---|
| | **Normalized S/N Ratio** | **Deviation Sequence** | **Normalized S/N Ratio** | **Deviation Sequence** |
| 1 | 0.9530 | 0.0470 | 0.2959 | 0.7041 |
| 2 | 0.7460 | 0.2540 | 0.6026 | 0.3974 |
| 3 | 0.7790 | 0.2210 | 0.3324 | 0.6676 |
| 4 | 0.6340 | 0.3660 | 0.9151 | 0.0849 |
| 5 | 0.7572 | 0.2428 | 0.9759 | 0.0241 |
| 6 | 0.8587 | 0.1413 | 0.1998 | 0.8002 |
| 7 | 0.4770 | 0.5230 | 0.4870 | 0.5130 |
| 8 | 0.0000 | 1.0000 | 0.0000 | 1.0000 |
| 9 | 0.6000 | 0.4000 | 0.2114 | 0.7886 |
| 10 | 0.9686 | 0.0314 | 0.6906 | 0.3094 |
| 11 | 0.7346 | 0.2654 | 0.8375 | 0.1625 |
| 12 | 0.9701 | 0.0299 | 0.8235 | 0.1765 |
| 13 | 0.7704 | 0.2296 | 0.6053 | 0.3947 |
| 14 | 0.5792 | 0.4208 | 0.2852 | 0.7148 |
| 15 | 0.8162 | 0.1838 | 1.0000 | 0.0000 |
| 16 | 1.0000 | 0.0000 | 0.5296 | 0.4704 |
| 17 | 0.9320 | 0.0680 | 0.1955 | 0.8045 |
| 18 | 0.9882 | 0.0118 | 0.6687 | 0.3313 |
| 19 | 0.9731 | 0.0269 | 0.8281 | 0.1719 |
| 20 | 0.8698 | 0.1302 | 0.4127 | 0.5873 |
| 21 | 0.7747 | 0.2253 | 0.8145 | 0.1855 |
| 22 | 0.8242 | 0.1758 | 0.5944 | 0.4056 |
| 23 | 0.4948 | 0.5052 | 0.1212 | 0.8788 |
| 24 | 0.8061 | 0.1939 | 0.5944 | 0.4056 |
| 25 | 0.8624 | 0.1376 | 0.9740 | 0.0260 |
| 26 | 0.7572 | 0.2428 | 0.1176 | 0.8824 |
| 27 | 0.8587 | 0.1413 | 0.7184 | 0.2816 |

### Calculation Of Grey Relational Coefficient (GRC)

To give the relationship in between the ideal (best) and actual normalized experimental results the grey relational coefficient is calculated. The grey relational coefficient can be expressed as,

$$\gamma_{0,i}(k) = \frac{\Delta_{min} + \xi.\Delta_{max}}{\Delta_{0i}(k) + \xi.\Delta_{max}} \text{.............} \quad \text{(Eq.7)}$$

### Gray Relation Coefficient for Surface Roughness

$$\therefore = \frac{0.5}{0.5 + \text{Deviational Sequance}}$$

$$\therefore = \frac{0.5}{0.5 + 0.0470}$$

$$\therefore = 0.9140$$

### a) Gray Relation Coefficient for MRR

$$\text{GRC} = \frac{0.5}{0.5 + \text{Deviational Sequance}}$$

$$\therefore \text{GRC} = \frac{0.5}{0.5 + 0.7041}$$

$$\therefore \text{GRC} = 0.4152$$

### Determination Of Weighted Grey Relational Grade (GRG)

The dim social evaluation is discovered by averaging the dark social coefficient with particular to every execution trademark. The general execution normal for the various reaction process relies on upon the computed dim social evaluation. The dark social evaluation communicated as,

$$\gamma(x_0, x_i) = \frac{1}{m}\sum_{i=1}^{m} \gamma(x_0(k), x_i\ (k)) \text{...........}$$

(Eq.8)

$$\gamma(x_0, x_i) = \frac{\text{GRC of Surface Roughness} + \text{GRC of Material Removal Rate}}{2}$$

$$\gamma(x_0, x_i) = \frac{0.9140 + 0.4152}{2}$$

$$\gamma(x_0, x_i) = 0.6646$$

Where $\gamma(x_0, x_i)$the grey relational grade for the i<sup>th</sup> experiment and m is the number of performance characteristics. This approach converts a multiple response process optimization problem into a single response optimization with the objective function of an overall grey relational grade.

***Table 7:** Gray Relation Coefficient and grade for Surface Roughness and MRR*

| SR.NO. | Surface Roughness | Material Removal Rate | GRG | RANK |
|---|---|---|---|---|
| | **Gray Relation Coefficient** | **Gray Relation Coefficient** | | |
| 1 | 0.9140 | 0.4152 | 0.6646 | **13** |
| 2 | 0.6631 | 0.5572 | 0.6101 | **19** |
| 3 | 0.6935 | 0.4282 | 0.5608 | **21** |
| 4 | 0.5773 | 0.8548 | 0.7161 | **9** |

| | | | | |
|---|---|---|---|---|
| 5 | 0.6731 | 0.9540 | 0.8135 | **5** |
| 6 | 0.7797 | 0.3845 | 0.5821 | **20** |
| 7 | 0.4888 | 0.4936 | 0.4912 | **23** |
| 8 | 0.3333 | 0.3333 | **0.3333** | **27** |
| 9 | 0.5556 | 0.3880 | 0.4718 | **25** |
| 10 | 0.9408 | 0.6177 | 0.7793 | **7** |
| 11 | 0.6532 | 0.7547 | 0.7040 | **12** |
| 12 | 0.9436 | 0.7391 | 0.8413 | **4** |
| 13 | 0.6853 | 0.5589 | 0.6221 | **18** |
| 14 | 0.5430 | 0.4116 | 0.4773 | **24** |
| 15 | 0.7312 | 1.0001 | 0.8656 | **2** |
| 16 | 1.0000 | 0.5152 | 0.7576 | **8** |
| 17 | 0.8803 | 0.3833 | 0.6318 | **16** |
| 18 | 0.9770 | 0.6015 | 0.7892 | **6** |
| 19 | 0.9490 | 0.7442 | 0.8466 | **3** |
| 20 | 0.7934 | 0.4598 | 0.6266 | **17** |
| 21 | 0.6894 | 0.7294 | 0.7094 | **11** |
| 22 | 0.7398 | 0.5521 | 0.6460 | **14** |
| 23 | 0.4974 | 0.3626 | 0.4300 | **26** |
| 24 | 0.7206 | 0.5521 | 0.6364 | **15** |
| 25 | 0.7842 | 0.9506 | **0.8674** | **1** |
| 26 | 0.6731 | 0.3617 | 0.5174 | **22** |
| 27 | 0.7797 | 0.6397 | 0.7097 | **10** |

## Prediction Of Grey Relational Grade Under Optimum Parameters

$$\eta_{opt} = \overline{T} + (\overline{A}_{(1/2/3)} - \overline{T}) + (\overline{B}_{(1/2/3)} - \overline{T}) + (\overline{C}_{(1/2/3)} - \overline{T})$$

$$\eta_{opt} = 06549 + (0.7187 - 0.6549) + (0.7048 - 0.6549) + (0.7175 - 0.6549) + (0.7127 - 0.6549)$$

$$+ (0.710.1 - 0.6549)$$

$$\eta_{opt} = 0.9444$$

***Table 8:****Optimal factor level for each response*

| **Control factor** | **Unit** | **SYMBOL** | **LEVEL** | **VALUE** |
|---|---|---|---|---|
| Peak current | Ampere | A | 2 | 60 |
| Pulse on time | Machine unit | B | 1 | 120 |
| Pulse off time | Machine unit | C | 2 | 50 |
| Wire feed | m / min | D | 2 | 8 |
| Wire tension | Kg-f | E | 1 | 4 |

***Table 9:*** *Optimal process parameter*

| Process parameter | Optimal process parameter | | |
|---|---|---|---|
| | **Initial** | **Predicted** | **Experiment** |
| | **A3B3C2D1E1** | | **A2B1C2D2E1** |
| IP | 90 | | 60 |
| Ton | 130 | | 110 |
| Toff | 50 | | 50 |
| WF | 4 | | 8 |
| WT | 4 | | 4 |
| GRG | 0.8674 | 0.9444 | 0.8801 |

## MICRO HARDNESS

There is a recast white layer formed on the EDMed machined surface. The surfaces are heavily rough because of the debris which are not flashed away completely from the machining zone. It indicates that the specimen's hardness near the outer surface can reach maximum than core hardness, but this hardening effect is due to the formation of the oxides $Cr_2O_3$, $ZrO_2$, $TiO_2$, $TiNiO_3$, carbides TiC and the deposition particles in the recast layer.

HV = Vickers hardness is,

$$HV = \frac{2F\sin\frac{136^\circ}{2}}{d^2} = 1.854\frac{F}{d^2}\ (approximately)$$

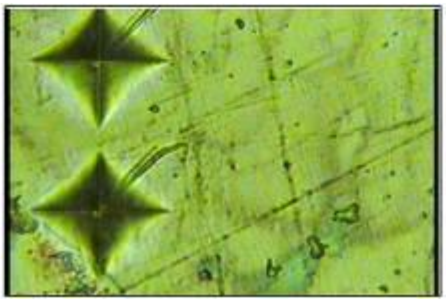


***Fig 7:*** *Diamond indentation after loading*

## RESULT AND DISCUSSION

Simulations are run as per Taguchi experimentation plan and respective values of Surface roughness and MRR for each simulation run is converted into the respective S/N ratios as per equation 1 and are given in Table 2,3. Data analysis is made using MINITAB R16@ software at the 95% of confidence. Main effect plots and interaction plots are used to determine the optimum factor levels for each response and results are shown in Figure 9.

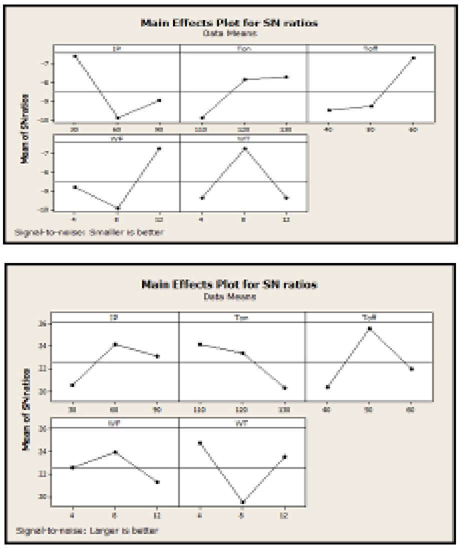
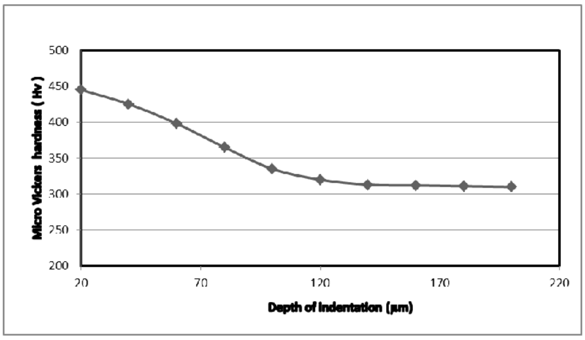


***Fig 8****:Main effect plots for S/N ratio*



**Graph 1:** *Micro hardness Vs Depth of indentation*

## CONCLUSION

In this study, the effect of process parameters on the response variables (MRR, SR and Micro Vickers hardness) of NITINOL was investigated experimentally in WEDM.

### 1) Material Removal Rate

The material removal rate is measured by the weight loss method in which material removal rate is mostly affected by the pulse off time because larger time between two successive sparks reduces the material removal rate.

### 2) Surface Roughness

The surface roughness of material during WEDM machining is mostly affected by the peak current. If peak current value is reaches maximum then surface become more rough due to high discharge energy during spark generation.

### 3) Micro Hardness

During WEDM machining material goes under thermo mechanical process so phase transformation occurs. Due to this there is hard layer is formed on outer side which is called as white layer and it varies up to core.

For multi objective optimization of optimal process parameters of Electro Discharge Machining (WEDM) for NITINOL shape memory alloy using Grey Relational Analysis, initial optimal combination A3-B3-C2-D1-E1 (IP=90, Ton=130, Toff=50, WF=4, WT=4) gives highest grey relational grade that is 0.8674. Thus, trial no. 25 shows the peak point for GRG, this is the initial optimum process parameters because it has highest grade.

4) As for every ANOVA table it uncovers that pinnacle current, wire encourage and wire pressure are most influencing procedure parameters on surface unpleasantness. Likewise the beat off time is the most influencing procedure parameter on Material Removal Rate.

5) Grey social examination (GRA) has been used to enhance both yield parameters all the while. The outcomes synopsis utilizing GRA is appeared as a part of Table10 beneath:

***Table 10:****Results of confirmation test*

| **Levels** | **Initial optimal combination**<br>**A3B3C2D1E1** | **Predicted** | **Experimental**<br>**A2B1C2D2E1** |
|---|---|---|---|
| Material Removal Rate | 36.2 | | 34.04 |
| Surface Roughness in µm | 3.12 | | 3.42 |
| GRG | 0.8674 | 0.9444 | 0.8801 |

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