Multi-Objective Optimization of WEDM Process Parameters of Ti-Ni Shape Memory Alloy for Biomedical Application

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Abstract - *The present work deals with the optimization of WEDM process parameters for machining Ti44.20-Ni55.80 shape memory alloy (SMA) for application of the biomedical. Effect of WEDM parameters viz. pulse on time (Ton), pulse off time (Toff), servo voltage, wire feed and wire tension on the response variables such as material removal rate, surface roughness and dimensional deviation is determined. As Ti-Ni SMA has captivating properties and bio-compatibility, has been considered. Eighteen experiments have been performed on WEDM based on an orthogonalarray of Taguchi method. Subsequently, the grey relational analysis (GRA) method is applied todetermine an optimal set of process parameters.*

It is observed that optimized set of parameters A2B1C3D3E2 viz. 110 machine unit pulse on time, 20 machine unit pulse off time, spark gap set voltage 40 V, wire feed 10 µm/sec and 4 µm/sec of wire tension determined by using GRA offers maximum MRR and minimum SR and DD. From the Analysis of Variance, it is seen that the process parameter pulse on time is the most significant parameter for multi-response optimization with a percentage contribution of 47.85%. Young'smodulus also checked for biocompatibility. Also, SEM image are taken to confirm the resultsoffering better surface quality.

Key Words: Wire electro-discharge machining, TiNi shape memory alloy, Taguchi Design, ANOVA, Grey relational analysis.

1. INTRODUCTION

Wire electrical discharge machining (WEDM) involves a series of complex physical process including heating and cooling. The electrical discharge energy, affected by the spark plasma intensity and the discharging time, will determine the crater size, which in turn will influence the machining efficiency and surface quality. Hence, the machining parameters, including pulse-on time, pulse-off time, table feed rate, flushing pressure, wire tension, wire velocity, etc. should be chosen properly so that a better performance can be obtained. However, the selection of appropriate machining parameters for WEDM is difficult and relies heavily on the operators' experience and machining parameters table provided by the machine-tool builder.Ti-Ni shape memory alloy is one of the widely used materials for various engineering products as well as in biomedical application because of its unique and captivating properties such as corrosion resistance, shape memory effect, good wear resistance and biocompatibility.

Selection of optimum machining parameter combinations for obtaining higher cutting efficiency and other dimensional accuracy characteristics is a challenging task in WEDM due to presence of large number of process variables and complicated stochastic process mechanism [1]. The temperature increases during machining of titanium because of low thermal conductivity and high chemical reactivity of titanium. Thus, the probability of wire breakage increases during machining of titanium when the cutting temperature at wire/work piece enhances [2]. Using current WEDM technology employing ultra-high frequency/short duration pulses it may be found the extremely low level of work piece damage [3]. The thermal stresses exceed the yield strength of the workpiece mostly in an extremely thin zone near the spark [4]. It has been reported that the MRR increases with increase in voltage and /or capacitance and higher values of wire tension and wire feed lead to better surface quality with the increase in voltage and capacitance, the energy supplied into the discharge gap increases which results in increasing MRR [6-7]. The use of traditional machining processes to machine hard composite materials causes serious tool wear due to abrasive nature of reinforcing particles thus shortening tool life [8, 9]. Although, nontraditional machining techniques such as water jet machining (WJM) and laser beam machining (LBM) can be used but the machining equipment is expensive, height of the work piece is a constraint, and surface finish obtained is not good [10, 11]. Titanium is also incredibly durable and long-lasting. When titanium cages, rods, plates and pins are inserted into the body, they can last for upwards of 20 years. Titanium non-ferromagnetic property is another benefit, which allows patients with titanium implants to be safely examined with MRIs [12-14]. WEDM has been acquiring wide acceptance for the machining of various conductive materials used in real applications such as metals, ceramics, silicon and metal matrix composites [15–19].

It can be seen from above mentioned research findings that not much work had been carried out in the area of multi-objective optimization of micro-WEDM process parameters for higher MRR and low surface roughness and less dimensional deviation.

In this context, the present work is carried out on;

i. Manufacturing of Ti44.20 Ni55.80SMA
ii. Mechanical properties of Ti44.20 Ni55.80for biocompatibility
iii. The effect of five WEDM process parameters viz. Ton, Toff, SV, wire feed and wire tension on MRR, SR and DD while machining Ti-Ni SMA.
iv. Multi-response optimization of WEDM process parameters for machining Ti-Ni SMA.
v. Surface integrity of WEDMed surfaces of optimized parameters for biocompatibility.

The work carried out is elucidated in the following sections.

2 Experimental Procedure

2.1 Sample preparation

Ti44.20 Ni55.80(Ti-Ni in short) SMAs were prepared by using the vacuum arc melting technique Titanium (purity 99.7 wt%) and nickel (purity 99.9 wt%), totaling about 120 gm, were melted and remeltedsix times in an argon atmosphere to confirm material homogeneity. Tungsten electrode was used for sparking and melting in an inertargon atmosphere. The vacuum up to 10-5 Torr vacuum was created before allowing the argon gas into the chamber and melting was started. The materials were melted in button shape followed byfurther melting into rectangular blocks of size 10 x 20 x 100 mm. Figure 1 shows energy dispersiveX-ray (EDX) analysis of as-cast Ti-Ni alloy clearly indicates the percentage of alloying elements ofTi and Ni alloy.

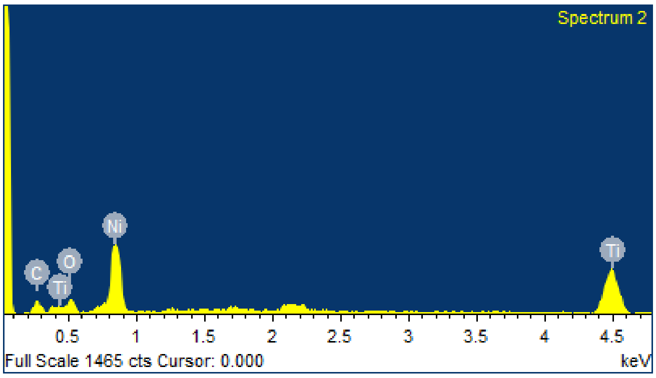

Fig. 1: EDX analysis of as-cast Ti44.20 Ni55.80 alloy

Shape memory effect to 33°C (austenite finish temperature) was achieved by subsequent heat treatment processes which include annealing to 525°C for 3 hours followed by aging at 375°C for 1 hour with water quench after each heat treatment on the material. The shape memory effect has the ability to return the material to a predetermined shape whenheated and also to create a more reliable barrier for Ni release from Ti-Ni. For the experimental analysis, WEDM is used toprepare a punch specimen of the size of 2mm×3mm×10mm.

A new biomedical material as Ti-Ni is recommended for stent, which is machined with the micro-WEDM. Physical and mechanical properties of materials are shown in Table 1.

Table 1: Physical and mechanical properties of materials

Properties	Ti-Ni SMA
Melting point (˚C)	1260
Density (Kg/*mm*3)	6400
Thermal conductivity (W/m*K)	10-15
Specific heat (J/Kg*K)	480
Transformation enthalpy (J/Kg)	29000
Modulus of elasticity (GPa)	55.632
Yield strength (MPa)	580.348
Ultimate tensile strength (MPa)	989.188
Elongation at fracture, martensite (%)	31.20

Transformation temperature range (C)	-100 to +110
Corrosion resistance	Excellent
Biological compatibility	Excellent

2.2 Parametric analysis based Taguchi Design

In Taguchi method, the raw data is transformed into S/N ratio values which determine the most significant parameters affecting the material MRR, SR and DD during the machining of Ti-Ni SMAs. The purpose of conducting an orthogonal experiment is to find the comparative significance of an individual factor, using analysis of variance (ANOVA) on the performance characteristics of the process under consideration.

2.3 Machining setup

The experimental set-up is shown in figure 2.

Fig.2: Experimental setup

A setup on WEDM machine has been developed on as shown in figure. The machine consist of wire electrode, spool to supply wire from which the zinc coated brass wire is constantly fed, tension arm for keeping wire in tension, wire guides for to guide thewire, dielectric nozzles for to supply dielectric fluids, wire collector spool for collecting used wire,Worktable to rest the workpiece material and tank to collect dielectric fluid. In this process, a metallic wire is fed into the workpiece, which is submerged in a tank of dielectric fluid as deionized water. The work table is CNC-controlled and moves in the x–y plane. A special Fixture was used to hold the workpiece. The zinc coated brass wire electrode of 250μm diameter has been used.

2.4 Machining parameter selection

The experiments were carried out based on the Taguchi design of experiments. Five controllable three-level factors and three response variables were considered. The selected process parameters and their identified levels for single pass cutting operation are given in Table 2. Nine experimental runs based on the L18 orthogonal array were performed (Refer Table 3).

Table 2: Controllable parameters considered

Parameters	Code	Level 1	Level 2	Level 3
Pulse on Time (Machine Unit)	Ton	100	110	--
Pulse off Time (Machine Unit)	Toff	20	30	40
Spark gap set Voltage (V)	SV	20	30	40
Wire Feed (m/min)	WF	4	8	10
Wire Tension (Machine Unit)	WT	4	8	12

Table 3: Experimental design using L18 orthogonal array

Experiment Number	Levels of process parameter settings				
	Ton	Toff	SV	WF	WT
1	100	20	20	4	4
2	100	20	30	8	8
3	100	20	40	10	12
4	100	30	20	4	8
5	100	30	30	8	12
6	100	30	40	10	8
7	100	40	20	4	8
8	100	40	30	10	8
9	100	40	40	4	12
10	110	20	20	10	12
11	110	20	30	4	4
12	110	20	40	8	8
13	110	30	20	8	12
14	110	30	30	10	4
15	110	30	40	4	8
16	110	40	20	10	8
17	110	40	30	4	12
18	110	40	40	8	4

3. Machining Performance Evaluation

3.1 Measurement of Material Removal Rate (MRR)

Material removal rate can be achieved by using weight difference of workpiece before and after machining. The weight loss of workpiece during the WEDM process was measured using Sansui digital weigh scale having least count 0.001mg. Knowing the density of Nitinol shape memory alloy (workpiece) material removal rate is estimated. The material removal rate is obtained by equation (1). In this equation, MRR is Material Removal Rate based on mm3/min. The material removal rate (MRR) is calculated as follows:

$$MRR\ (mm^3/min) = \frac{W_1 - W_2}{\rho_{nitinol}}\ x \frac{1}{T_m} x\ 1000 ------ \text{Eq.}(1)$$

Where W1 is the weight of the workpiece before machining, W_2 is the final weight of the workpiece after machining in gram, ρ_{niinol} is the density of Nitinol shape memory alloy in gm/cm3 (6.45gm/cm3) and Tm is the machining time in minutes.

3.2 Measurement of Surface Roughness (Ra)

The surface roughness was measured as per JIS 2001 standard by using 'Mitutoyo' surface roughness tester SJ-210 model shown in Fig.2. The average surface roughness (Ra), are considered for the current study. GRA solves multi-attribute decision-making problems by combining the entire range of performance attribute values being considered for every alternative into one single value. The cutoff length of 0.8 mm was selected and an evaluation length of 4 mm was used to measure the surface roughness with a stylus speed of 0.25 mm/s.

3.3 Measurement of dimensional deviation (DD)

In the WEDM process, profile traced by the wire and the job profile is not same. The perpendicular distance between the actual profile and the profile traced by the wire is equal to half of the width of the cut.Thus the actual job produced by WEDM is either undersized or oversized depending upon whether the job is a punch or die. The orientation of this wire offset (i.e., left or right with respect to the programmed path) depends upon the direction (clockwise or counter clockwise) of cutting and type of job (i.e., die or punch). The term ''dimensional deviation'' has been used as response parameter during a cutting experiment in WEDM with zero wire offset. But, 'wire offset' is a controlled setting in WEDM part programming to eliminate or minimize dimensional inaccuracy during actual machining by Dimensional deviation measured using Mitutoyo made digital micrometer having least count of 0.001 mm. And corresponding % dimensional deviation can be calculated using Eq.2.

$$\% \text{ Dimensional Deviation} = \frac{\text{Observed Value} - \text{Actual Value}}{\text{Actual Value}} x\,100 \quad ---\text{Eq. (2)}$$

4. Experimental Results, Analysis and Discussion

The experimental results of mean and their associated S/N ratios values are shown in Table 4.

Table 4: S/N ratio for MRR, SRand DD

Exp. No.	Average MRR (mm3/min)	S/N Ratio	Average SR (Ra) (µm)	S/N Ratio	Dimensional Deviation (%)	S/N Ratio
1	0.7245	-2.799	1.21	-1.656	0.875	1.1598
2	1.2548	1.971	1.952	-5.810	0.881	1.1005
3	1.235	1.833	1.587	-4.012	0.712	2.9504
4	0.6847	-3.290	1.755	-4.886	0.689	3.2356
5	0.5598	-5.039	1.32	-2.411	0.779	2.1693
6	0.7541	-2.451	1.154	-1.244	1.102	-0.8436
7	0.1988	-14.032	0.902	0.896	0.652	3.7150
8	0.1792	-14.933	1.25	-1.938	0.498	6.0554
9	0.1185	-18.526	1.014	-0.121	0.56	5.0362
10	3.507	10.899	2.784	-8.893	0.56	5.0362
11	1.7051	4.635	2.521	-8.031	0.795	1.9927
12	2.8851	9.203	2.102	-6.453	0.555	1.8841
13	2.4025	7.613	2.568	-8.192	0.422	3.8628
14	4.0065	12.055	2.265	-7.101	0.441	3.5045
15	1.7255	4.738	1.489	-3.458	1.000	-0.9065
16	0.6422	-3.847	2.562	-8.172	0.333	6.0554
17	0.5652	-4.956	1.94	-5.756	0.341	5.8146
18	0.4687	-6.582	1.987	-5.964	0.776	0.0961

4.1Analysis of variance (ANOVA) and Mean effect plots

To calculate the S/N ratios, larger the better function is used for MRR and smaller the better for SR, DD. The S/N ratio for the larger the better type and smaller the better type of response can becomputed by using Eq. (3) and Eq. (4), respectively as,

n = -10 Log_{10} [mean of sum squares of reciprocal of measured data}

$$n = -10\,Log_{10}\left(\frac{1}{R}\sum_{j=1}^{R}(1/y_j^2)\right) -----\text{Eq3}$$

n = -10 Log_{10} [mean of the sum of squares of measured data]

$$n = -10\, Log_{10}\left(\frac{1}{R}\sum_{j=1}^{R} y_j^2\right) ------ \text{Eq. (4)},$$

Where, y_j is the response value

The results were statistically analyzed using ANOVA at 95 % confidence level and the effects were evaluated. P-value establishes whether the process parameter is significant or not at a particular confidence level. For a 95 % confidence level P-value must be less than 0.05 for the significant parameter.

4.1.1 Analysis of Material Removal Rate

From ANOVA table (Refer Table 5) indicates that pulse on time and pulse off time are the most significant parameters with a percentage contribution of 35.39% and 35.39% respectively. Other parameters have a negligible effect on MRR.

Table 5. Analysis of Variance for MRR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Ton	1	8.2667	8.26672	14.00	0.006
Toff	2	8.2667	4.11882	6.97	0.018
SV	2	0.1185	0.05925	0.10	0.906
WF	2	1.9230	0.96152	1.63	0.255
WT	2	0.0862	0.04308	0.07	0.930
Error	8	4.7249	0.59062		
Total	17	23.3570			

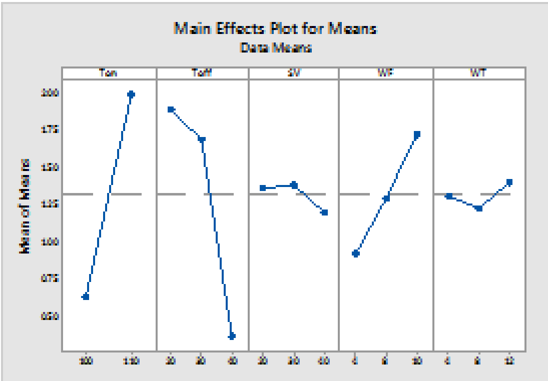

fig. 3: Effect of process parameters on MRR

From the above method, more amount of material is removed when pulse on time is increased. It has been found that at a high level of voltage (40 V) due to high gap pollution and insufficient flushing condition cause to decrease in MRR within the work interval.

4.1.2 Analysis of Surface Roughness

ANOVA Table 6 results revealed that the pulse on time is the most significant parameter for the surface roughness with a percentage contribution of 61.27%. All other parameters are not as significant as their effect on SR is less.

Table 6: Analysis of Variance for SR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Ton	1	3.6216	3.62164	35.06	0.000
Toff	2	0.5352	0.26761	2.59	0.136

SV	2	0.5524	0.27622	2.67	0.129
WF	2	0.2337	0.11686	1.13	0.369
WT	2	0.1409	0.07044	0.68	0.533
Error	8	0.8263	0.10329		
Total	17	5.9102			

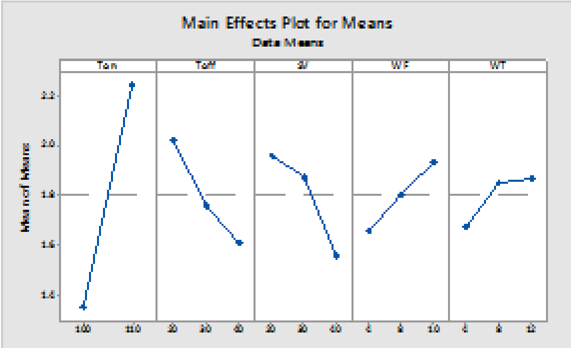

fig. 4: Effect of process parameters on SR

The effect of Ton, Toff, SV, WF and WT on SR are as shown in Figure 4. Increase in discharge energy with an increase in Ton leads to eroding the workpiece material at a faster rate due to the high temperature of spark. This results in a higher value of surface roughness. A fine value of surface roughness is achieved at 40V. At a higher value of voltage, Carbon gets formed on the surface to be machined which leads to the components inaccuracies.

4.1.3 Analysis of dimensional deviation

Table 7 shows the ANOVA results for dimensional deviation. The dimensional deviation is significantly affected by spark gap set voltage that contributes 28.05%. Percentage contribution of pulse on time is 0.25% which indicates that change in pulse on time has very lower effect on dimensional deviation.

Table 7: Analysis of Variance for DD

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Ton	1	0.001606	0.001606	0.11	0.754
Toff	2	0.145182	0.072591	4.76	0.044
SV	2	0.178684	0.089342	5.85	0.027
WF	2	0.044340	0.022170	1.45	0.290
WT	2	0.144921	0.072461	4.75	0.044
Error	8	0.122112	0.015264		
Total	17	0.636846			

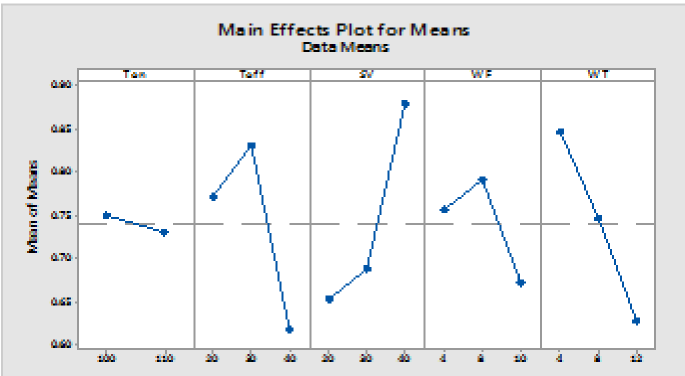

Figure 5. Effect of process parameter on the DD

Figure 5 shows the effect of process parameter on the dimensional deviation. A higher value of wire tension produces the less wire vibration & forms narrow width. In case of wire feed value of dimensional deviation first increase & then decrease.

5. Grey Relational Analysis for the Experimental Results

WEDM has a number of parameters which affect the performance characteristics. Thus, it is necessary to find the optimal condition for machining of Ni-Ti Alloy, which can be found by multi response analysis in grey rational method. The most influential factors for an individual quality target of cutting operation can be identified by analyzing the grey relational grade matrix.

Grey relational analysis is carried out in the following steps

1) Normalizes the experimental results of each performance characteristic.

2) Determination of deviation sequence

3) Calculate the grey relational coefficient (GRC)

4) Calculate the grey relational grade (GRG)

5) Selection of the optimal level of parameters and Analysis of variance of GRG

6) Confirmation Test

Step 1. Normalizes the experimental results of each performance characteristic

The first step of GRA consists of normalizing the experimental data i.e. S/N ratio in order to transfer the original sequence to a comparable sequence (i.e. Dimensionless data sequence). Measured values of response characteristics are normalized between zero to one. There are different methods of data processing in GRA depending on the characteristics.

Table 8: Normalization for MRR, SR, KW, and DD

Expt. No.	MRR	SR	DD
Ref. sequence	1.0000	1.0000	1.0000
1	0.514	0.261	0.703
2	0.670	0.685	0.712
3	0.666	0.501	0.446
4	0.498	0.591	0.405
5	0.441	0.338	0.558
6	0.526	0.219	0.991
7	0.147	0.000	0.336
8	0.117	0.290	0.000
9	0.000	0.104	0.146
10	0.962	1.000	0.146
11	0.757	0.912	0.584
12	0.907	0.751	0.599
13	0.855	0.928	0.315
14	1.000	0.817	0.366
15	0.761	0.445	1.000
16	0.480	0.926	0.000
17	0.444	0.680	0.035
18	0.391	0.701	0.856

The material removal rate is the larger the better type characteristics. Hence, its original sequence can be normalized by using Eq. (5).

$$x_i^*(k) = \frac{x_i^0(k) - min\ x_i^0(k)}{max x_i^0(k) - min\ x_i^0(k)} \quad --- \text{Eq. (5)}$$

In contrast, the surface roughness, kerf width and dimensional deviation are "Smaller the better" type characteristics. Hence its original sequence can be normalized by using Eq. (6).

$$x_i^*(k) = \frac{max x_i^0(k) - x_i^0(k)}{max x_i^0(k) - min\ x_i^0(k)} \quad -- \text{Eq. (6)}$$

Where, Xi0(k) represents an original sequence, Xi*(k) represents comparability sequence,

i = 1,2,3,…m [m be the total no. experiment performed],

k =1,2,3,…n [n be the number of parameter considered], In present work m=9 and n=4.

Step2. Determination of deviation sequence

Before calculating GRG it is necessary to calculate deviation sequence $\Delta_{oi}k$, which is the absolute difference between the reference sequence x0* (k) and the comparability sequence xi*(k) after normalization.

$$\Delta_{oi}k = |x_0^*(k) - x_i^*(k)| \qquad --- \text{Eq. (7)}$$

Note: Reference sequence x_0^* (k)=1

Table 9: The deviation sequence

Deviation sequence				GRC and GRG				
Deviation sequence	$\Delta_{01}(01)$ MRR	$\Delta_{01}(02)$ SR	$\Delta_{01}(04)$ DD	MRR	SR	DD	Grade Values	Rank
No.1, *i=1*	0.486	0.739	0.297	0.507	0.403	0.627	0.513	12
No.2,i=2	0.330	0.315	0.288	0.603	0.614	0.634	0.617	9
No.3,i=3	0.334	0.499	0.554	0.599	0.501	0.474	0.525	11
No.4, *i=4*	0.502	0.409	0.595	0.499	0.550	0.457	0.502	13
No.5,*i=5*	0.559	0.662	0.442	0.472	0.430	0.531	0.478	14
No.6, *i=6*	0.474	0.781	0.009	0.513	0.390	0.982	0.628	7
No.7,*i=7*	0.853	1.000	0.664	0.370	0.333	0.430	0.377	16
No.8,*i=8*	0.883	0.710	1.000	0.362	0.413	0.333	0.369	17
No.9, *i=9*	1.000	0.896	0.854	0.333	0.358	0.369	0.354	18
No.10, *i=10*	0.038	0.000	0.854	0.930	1.000	0.369	0.766	1
No.11,i=11	0.243	0.088	0.416	0.673	0.850	0.546	0.690	5
No.12,i=12	0.093	0.249	0.401	0.843	0.667	0.555	0.688	6
No.13, *i=13*	0.145	0.072	0.685	0.775	0.875	0.422	0.691	4
No.14,*i=14*	0.000	0.183	0.634	1.000	0.732	0.441	0.724	2
No.15, *i=15*	0.239	0.555	0.000	0.676	0.474	1.000	0.717	3
No.16,*i=16*	0.520	0.074	1.000	0.490	0.872	0.333	0.565	10
No.17,*i=17*	0.556	0.320	0.965	0.473	0.609	0.341	0.475	15
No.18, *i=18*	0.609	0.299	0.144	0.451	0.626	0.776	0.618	8

Step3. Calculate the grey relational coefficient (GRC)

Grey relational coefficient denotes the correlation between the best and actual experimental results. The GRC can be expressed by Eq. (8).

$$\gamma\left(x_0^*(k), x_i^*(k)\right) = \frac{\Delta_{min} + \zeta.\Delta_{max}}{\Delta_{0i}(k) + \zeta.\Delta_{max}} \quad --- \text{Eq.}(8)$$

And,

$$0 < \gamma\left(x_0^*(k), x_i^*(k)\right) \leq 1$$

Where, $\Delta_{0i}(k)$ is the deviation sequence of the reference sequence $x_0^*(k)$ and comparability sequence $x_i^*(k)$ (Refer Eq. 5).

And, $\Delta_{max} = max|x_0^*(k) - x_i^*(k)| = 1$

$\Delta_{min} = min|x_0^*(k) - x_i^*(k)| = 0$

ζ = Distinguishing coefficient, $\zeta \in (0, 1)$ for present study, ζ was set as 0.5 based.

Step4. Calculate the grey relational grade (GRG)

The Grey relational grade help to determine the best set of parameters with which experiment is performed i.e. higher GRG shows that the concerned parameter combination is very nearer to the optimum value. An average some of the grey relational coefficients is termed as GRG and can be expressed by Eq. (9).

$$\gamma(x_0^*, x_i^*) = \frac{1}{m}\sum_{i=1}^{m} \gamma(x_0^*(k), x_i^*(k)) -- \text{Eq.}(9)$$

Where,

$\gamma(x_0^*, x_i^*)$ is the GRG for j experiment, j = 1,2,3,..n

m = no. of performance characteristics = 4

Step5. Selection of the optimal level of parameters and Analysis of variance of GRG

Table 8 shows the grey relational grade for all comparability sequence, larger the grey relational grade, better the corresponding multi-objective characteristics, the value of GRG for experiment No. 9 is more which indicate that the process parameter "Setting of experiment A2B1C3D3E1" offers best multiple performance characteristics among the eighteen experiments.

The response table based on Taguchi method for the S/N ratios of the grey relational grade is shown in Table 10. The effect of each level of process parameter on grey relational grade can be identified from the table. From the response table for GRG; the best set of combination of the process parameter is A2B1C3D3E1.

Table 10: Response table for the grey relational grade (GRG)

Levels	Ton	Toff	SV	WF	WT
1	0.485	0.633	0.569	0.542	0.592
2	0.659	0.623	0.559	0.578	0.576
3	-	0.503	0.588	0.596	0.548
Max	0.659	0.633	0.588	0.596	0.592
Min	0.485	0.503	0.559	0.542	0.548
Delta	0.174	0.130	0.029	0.055	0.044
Rank	1	2	5	3	4
Total mean value of GRG is 0.575					

Step5.1. Analysis of results

The obtained GRG is considered a single response for the designed experiment and analysis of variance is carried out in to know which parameters significantly affect the multi-objective response. ANOVA for GRG is given in Table 10. From the table, it can be seen that pulse on time is most significant for the optimum multi-response. All other parameters have less effect on machining performance.

Table 11: ANOVA of GRG

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Ton	1	0.137009	0.137009	63.15	0.000
Toff	2	0.113981	0.056990	26.27	0.000
SV	2	0.002688	0.001344	0.62	0.562
WF	2	0.009361	0.004681	2.16	0.178
WT	2	0.005917	0.002959	1.36	0.309
Error	8	0.017357	0.002170		
Total	17	0.286312			

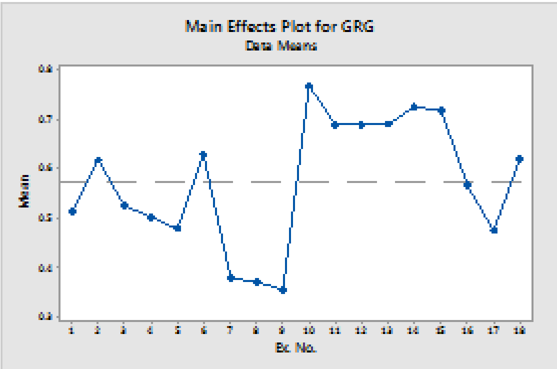

Fig. 6: Main effects plot for GRG

Figure 6 shows the main effects plot for GRG. The maximum GRG values were observed at a gap voltage of 20 V, Ton time 110, Toff time 20, wire feed of 10µm/sec and wire tension of 12. Hence the combination of these process parameter values gives the optimal result for multi-response.

Step6. Confirmation Test

After evaluating the optimal parameters set, the next step is to predict and variety an improvement of quality characteristics. The optimal Grey Relational grade η_{opt} is predicted using Equation 10

$$\eta_{opt} = \overline{T} + \left(\overline{A}_{(1/2/3)} - \overline{T}\right) + \left(\overline{B}_{(1/2/3)} - \overline{T}\right) + \left(\overline{C}_{(1/2/3)} - \overline{T}\right) + \left(\overline{D}_{(1/2/3)} - \overline{T}\right) -- Eq. \quad 10$$

Where,

$\overline{T}$ = Total mean of the response

$\overline{A}_{(1/2/3)}$, $\overline{B}_{(1/2/3)}$, $\overline{C}_{(1/2/3)}$, $\overline{D}_{(1/2/3)}$ = Mean of GRG at an optimal level (i.e. maximum values of response at the first or second or third level of parameters A, B, C, and D respectively)

In present work, $\overline{T}$= 0.541

η_{opt}= 0.8150

Finally, a confirmation test is carried out using the optimum combination of the parameter (A3B3C3D1). Table 12 shows the comparison of predicted GRG with the actual one obtained from the experimental results of the optimal test parameter. The improvement in GRG from initial parameter combination A2B1C1D3E3 (110, 20, 20V, 20μm/sec and 12) to the optimal parameter combination A2B1C3D3E1 (110, 20, 40V, 10 μm/sec, 4) is 0.021, which is 4.961% of initial setting. This improvement is observed because of the increase in wire feed from 10μm/sec to 20μm/sec.

Table 12: Predicted and Experimental Results

Process Parameters	Initial Setting	Predicted Value	Experimental Validation
Optimal parameters	A2B1C1D3E3	A2B1C3D3E1	A2B1C3D3E1
Ton	110	110	110
Toff	20	20	20
SV	20	40	40
WF	10	10	10
WT	12	4	4
Grey Relational Grade	0.766	0.8150	0.8040
Improvement of the grey relational grade = 4.961%			

9. CONCLUSIONS

The effect of pulse on time, pulse of time, spark gap voltage wire feed and wire tension on micro-WEDM performance characteristics in the machining of $Ti_{44.20}$-$Ni_{55.80}$

SMA has been experimentally investigated. The Taguchi method integrated with grey relational analysis was used to optimize the micro-WEDM process parameters for Ni-Ti SMA.

Based on the results of the experimental study, the following conclusions are drawn

1) $Ti_{44.20}Ni_{55.80}$ SMA is more suitable for the biomedical implant (stent), having Young's modulus (55.632 GPa) is less than other implant material like Ti (E = 105 GPa) and SS316L (210 GPa).

2) The ANOVA tables for MRR and SR reveal that pulse on time is the most significant factor with a percentage contribution of 35.39 and 61.27 respectively. DD reveal that spark gap set voltage is the most significant factor with a percentage contribution of 28.04.

3) The ANOVA of GRG for multi-performance characteristics reveals that the percentage contribution of pulse on time is 47.85%. Hence capacitance is an identically most significant parameter. Increase in pulse on time, discharge energy per pulse results in higher MRR, SR and DD.

4) Using the GRA initial setting (A2B1C1D3E3), grey relational grade 0.766 is increased by using a new optimum combination (A2B1C3D3E1) to 0.8040. It means that there is an increment in the grade of 4.961%. Therefore, using the GRA approach of analysis, process parameters have been successfully optimized for better machining performance characteristics.

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