



Article Effect of Near-Dry WEDM Process Variables through Taguchi-Based-GRA Approach on Performance Measures of Nitinol

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Abstract: The machining of Nitinol shape memory alloys (SMA) through conventional machining techniques imposes several challenges due to the alloys' comprehensive mechanical qualities. Wire electrical discharge machining (WEDM) process is a non-conventional machining technique that is suitable mainly for producing complex shape geometries with excellent surface features for difficultto-cut materials. The current study attempted the use of a near-dry WEDM process for Nitinol SMA with the consideration of multiple response variables. The studied literature and machine capabilities have identified input factors of pulse-on-time (T_{on}), pulse-off-time (T_{off}), and current and output factors of MRR, SR, and RLT. Through the Taguchi approach, a total of nine experimental trials were designed to analyze the performance of the process. The statistical significance of input factors on the performance measures was studied with the help of ANOVA techniques. Statistical analysis for all the output measures has shown that the generated regression terms had a significant influence. For single output measures, the current was found to have a substantial effect on both MRR and SR, while Toff was the most significant contributor in the case of RLT. The obtained results of residual plots for all performance measures implied good ANOVA results. The effect of near-dry WEDM variables was studied on output measures through main effect plots. Grey relational analysis (GRA) has been employed to attain optimal parametric settings of multiple performance measures. GRA technique for the optimal parametric settings of simultaneous performance measures of MRR, SR, and RLT was found to have a Ton of 30 µs, Toff of 24 µs, and current of 4 A. Validation trials were conducted to check the adequacy of the GRA technique. The minor acceptable deviation was recorded among the anticipated and recorded values. This clearly reveals the acceptability of the integrated approach of the Taguchi-Grey method. The surface morphology for the near-dry and wet-WEDM has also been investigated through scanning electron microscopy (SEM). The author considers that the present study will be beneficial for users working in WEDM and near-dry WEDM processes for hard machining materials.

Keywords: near-dry WEDM; shape memory alloy; Nitinol; grey relational analysis; surface topography

1. Introduction

With a mechanical or thermal load application, certain metallic and polymeric materials with the unique feature of shape memory revert back to their original shape after deforming due to temperature or stress [1–3]. These kinds of materials that possess shape recoveries are called shape memory alloys (SMAs). SMAs possess shape memory effect (SME), pseudo-elasticity, superior biocompatibility, and super-elasticity [4,5]. Nickeltitanium SMA, commonly referred to as Nitinol SMA, have gained a lot of popularity owing to their unique characteristics and acceptability for a wide range of applications [6,7]. Nitinol's superior properties include excellent corrosion resistance, outstanding biocompatibility, SME, wear resistance, and pseudo-elasticity [8,9]. Higher tensile and lower yield



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). strength of Nitinol exhibit great elongation. Nitinol generates a protective TiO₂ layer, which becomes useful in restricting the release of Ni ions in biofluid [10,11]. This is what makes the wide acceptability of Nitinol material for biomedical applications. The machining of Nitinol imposes several challenges due of its comprehensive mechanical qualities, such as higher toughness and strength, and sensitivity to phase transition temperatures [12,13]. The traditional machining techniques impose several drawbacks like excessive tool wear, tool breakage, chip burning, surface defects, and, more importantly, loss of SME [14,15]. Due to the widespread usage of Nitinol in various applications, the finished product requires complex shape geometries and an excellent surface finish.

The wire electrical discharge machining (WEDM) process is suitable for producing complex shape geometries with excellent surface features [16]. It can machine any hard conductive material regardless of its hardness [17]. Himanshu et al. [18] employed the WEDM process for creating complex shape profiles for Nitinol SMA. Their finding revealed that WEDM was suitable for creating their complex shape profiles with significant contributions of pulse-on-time (T_{on}) input factors, voltage, and pulse-off-time (T_{off}) . Chaudhari et al. [19] employed the WEDM process to machine the Nitinol SMA. They concluded that the most important factors impacting surface roughness (SR) and microhardness were determined to be T_{off} and current. The WEDM method is majorly categorized in three key areas by means of the usage of the dielectric medium. It includes dry, wet, and near-dry WEDM (NDWEDM) variants. Along with the environment-associated factors, NDWEDM process performance was improved by using a minimal amount of dielectric fluid and a larger use of compressed air or gas in a friendly environment [20]. Sampath et al. [21] performed experimental studies on eco-friendly NDWEDM of M2-HSS materials. For appropriate cooling and to flush out debris, a minimal quantity of dielectric liquid and a higher amount of helium-mist were utilized as the dielectric medium. The obtained results have shown that a rise in voltage and pulse width amplified MRR and SR responses. The results of confirmation runs have revealed the successful performance of the NDWEDM process. Chaudhari et al. [22] analyzed the effect of the NDWEDM approach to lessen the environmental impact of wet WEDM. A parametric optimization was conducted with input factors of current, Ton, and Toff. Their obtained results from SEM surfaces revealed better surface features while using a near-dry WEDM process in comparison with the conventional WEDM process. Boopathi et al. [23] studied MRR and SR of machining by the NDWEDM process. Due to the rapid debris clearance and high oxygen-mist velocity, the highest MRR and least SR were attained by using the near-dry WEDM process. Myilsamy and Boopathi [24] compared near-dry and cryogenically cooled NDWEDM machining in their study. NDWEDM has significantly improved the performance by means of 29% improvement in TWR, 15.6% improvement in MRR, and 7.23% improvement in SR values in comparison with the conventional process. Another study conducted by Gunasekaran et al. [25] investigated the performance of NDWEDM by considering various compressed gas mediums. Their study used Mo wire to obtain precise machining conditions for Inconel 718. Kannan et al. [20] examined the effects of cryogenically treated Inconel 718 work material on the characteristics of NDWEDM. Argon-mist, a mixture of pressurised argon gas and a small amount of tap water, was used along with a reusable Molybdenum wire tool. Their finding revealed that an increase in pulse duration and current resulted in higher MRR and SR, while an increase in T_{off} resulted in a drop in both MRR and SR. To determine the best parameter settings for enhancing both machining features, the TOPSIS approach for order of preference by similarity to the ideal solution was used.

The literature thus suggested that appropriate levels of WEDM variables to attain multiple responses can be achieved by deriving optimal parametric settings through parametric optimizations. Grey relational analysis (GRA) is one such optimization technique that is easy to implement and provides robust solutions while dealing with multiple response measures. Piyush et al. [26] used the GRA approach to attain the optimal parametric setting of input factors for performance measures of MRR and SR for the WEDM process of Ni55.8Ti SMA. Experimental trials have been used to validate predicted values derived using GRA at an ideal setting, and they demonstrate a very close relationship. Rahman et al. [27] analysed the interaction between input factors of face milling of Ti6Al4V alloy for selected responses. For multi-objective optimization, Taguchi-based GRA has revealed substantial improvements in all responses, such as tool life, SR, and cutting forces, which were improved by 55.81%, 6.12%, and 23.98%, respectively. Another study conducted by Alhodaib et al. [28] used the GRA technique to find the optimal parametric settings during the powder mixed-EDM process of nickel-based superalloy. Least deviation between actual trials and GRA predicted results have shown the suitability of the GRA approach for multiple performance measures.

The detailed analysis of the studied literature and machining of hard materials were largely attempted by using the wet WEDM process. Very limited work has been carried out by using a near-dry WEDM process for difficult-to-cut materials, including Nitinol SMA, for multiple response measures. Thus, the current study attempted the use of a near-dry WEDM process for Nitinol SMA with the consideration of multiple response variables. The studied literature and machine capabilities have identified input factors of Ton, Toff, and current and output factors of MRR, SR, and RLT. The combined influence of output factors has been studied using the GRA technique. Section 2 of the current study represents the selection of materials with the composition, plan of the experiments, selection of input variables along with their levels, and evaluation of performance measures. In Section 3, results were obtained per experimental plan with detailed analysis through statistical findings, main effect plots, and simultaneous optimization through the GRA approach. The surface morphology for the near-dry and wet WEDM has also been investigated. In the last section, conclusions drawn from the study were represented in detail. The author considers that the present study will be beneficial for users working in WEDM and near-dry WEDM processes for hard machining materials.

2. Materials and Methods

This section describes the selection of materials, the plan of the experiments, and the evaluation of performance measures. Section 2.1 mentions all the details pertaining to the experimental setup, selection of input variables, their levels, and detailed plans for actual trials. Section 2.2 contained the methodology for the determination of the selected performance measures.

2.1. Experimental Plan and Design of Experiments

In the present study, the near-dry WEDM process was employed to perform the experimental trials using the Concord make DK 7732 setup. The selected work material of Nitinol SMA was used in the form of a rod having a diameter of 10 mm. The selected work material of Nitinol SMA consisted of two major compositions in weight % as: a Ni content of 55.7% and Ti as a reminder. During the experimentations, 2 mm thick parts were cut through a near-dry WEDM process using Mo wire as a tool electrode. The WEDM method is categorized in three key areas by means of the usage of the dielectric medium. It includes: (1) dry WEDM, which requires any suitable compressed gas as a dielectric medium; (2) wet WEDM, which works on the basis of only dielectric fluid; (3) near-dry WEDM, which utilizes both the medium of compressed gas and dielectric fluid with least quantity [29]. The NDWEDM process does not produce toxic fumes like wet WEDM process. The NDWEDM process is a capable and robust technique that provides insignificant health hazards [30]. Figure 1 displays the schematic of the employed experimental setup of the present work for near-dry WEDM.



Figure 1. Schematic of the near-dry WEDM.

The studied literature and machine capabilities have identified T_{on} , T_{off} input factors, and current. For the appropriate selection of the range of input factors, preliminary experiments were conducted. On the basis of the results from preliminary trials, studied literature, and machine capabilities, three key levels were identified, as shown in Table 1. The performance of these selected input factors was analyzed through the three key performance output factors of MRR, SR, and RLT. By considering the key features of Taguchi's methodology, 3 factors and 3 level designs with Taguchi's L₉ technique have been used. Thus, a total of 9 trials were designed to analyze the performance of the process. Taguchi's methodology gives minimum experimental trials with robust parametric amalgamations [31]. This, in turn, saves time and costs and also provides a relationship between the design variables and performance measures [32]. However, all the trials were conducted three times to attain the desired accuracy in the output factors.

Table 1. Input factors of near-dry WEDM.

Parameters	Values
Pulse-on time (µs)	30; 60; 90
Pulse-off time (µs)	8; 16; 24
Current (A)	2; 4; 6
Wire Electrode	Molybdenum
Wire Diameter (mm)	0.18

2.2. Performance Measures

In the present study, the performance of the selected input factors was analyzed through the three key performance output factors of MRR, SR, and RLT.

The MRR was determined by means of evaluating the weight loss from the work material. Equation (1) represents the formula for the determination of MRR.

$$MRR = \frac{\Delta W * 10,000}{\rho * t}$$
(1)

Here, ΔW , ρ , and t represent the weight loss during each trial, the density of work material (6.5 g/cm³), and time in seconds, respectively.

SR of the machined components was determined by using an SR tester SJ410. The SR evaluation criteria were set as: a cut-off length of 2.5 mm, evaluation length of 8 mm, and a lowest stylus speed of 0.1 mm/s for better accurate results. SR was determined at four locations for each sample, and their mean value was taken into consideration for

higher accuracy and precision. RLT of all samples were determined by employing the field emission scanning electron microscope (FESEM) technique. The morphological analysis of the individual sample was carried out by a FESEM (Zeiss Ultra 55) operating at 5 keV. Prior to analysis, each sample was cleaned with acetone, isopropanol, and distilled water to remove any contamination over the sample. Furthermore, the samples were dried at room temperature before being loaded on the carbon tape for FESEM analysis. The chemical acetone, isopropanol, and distilled water were purchased from Sigma-Aldrich and were used without any further purification. Minitab v17 software was employed to obtain the means of output factors and statistical analysis.

2.3. Grey Relational Analysis

Deng has established a decision-making method on the basis of grey theory, generally termed grey relational analysis (GRA) [33]. GRA has been developed to obtain the optimal settings of process variables by means of converting multiple variables into an individual grey relational grade (GRG) [34]. A larger GRG number depicts the robust relationship between the reference and comparability order. GRA was employed for the simultaneous optimization of the selected output factors. Pursuant to this, GRA was used to create a single objective function from all the output factors. In comparison with the other techniques to obtain an optimal solution for multiple objectives, GRA method provides a key advantage as there is no specific constraint in sample size and normally distributed data and their computational method are easy as well. GRA method is adequate to provide a robust solution with least acceptable deviation. In addition, GRA technique provides additional benefits owing to the low requirements for data size. In the present study, Taguchi's approach was coupled with GRA technique. Individual objectives were converted into a solitary function through S/N ratios. Pursuant to this, MRR was assigned with higher-the-better characteristics, and SR and RLT were assigned with lower-the-better characteristics.

3. Results

This section provides a detailed investigation of the derived results from experimentations by following Taguchi's approach. Table 2 represents the experimental plan along with the performance measure values of MRR, SR, and RLT. The maximum value of MRR was found at 0.8675 mm3/sec, and the lowest value was recorded as 0.3744 mm^3 /sec. For the other response of SR and RLT, values in the range of 3.79 µm to 6.81 µm and 5.74 µm to 9.89 µm were achieved. These derived results were analyzed in the subsequent sections for statistical significance, adequacy of statistical findings, the influence of input factors on output measures, simultaneous optimization, and machined surface morphology of the near-dry WEDM process.

Cr. No.	Input Factors			Output Factors			S/N Ratios		
Sr. 1NO.	T _{on} (μs)	T _{off} (μs)	Current(A)	MRR(mm ³ /sec)	SR(µm)	RLT(µm)	MRR	SR	RLT
1	30	8	2	0.3997	3.91	8.15	-7.966	-11.844	-18.222
2	30	16	4	0.5646	4.87	6.61	-4.965	-13.742	-16.407
3	30	24	6	0.6029	5.51	5.74	-4.396	-14.824	-15.181
4	60	8	4	0.7114	5.11	8.12	-2.958	-14.168	-18.191
5	60	16	6	0.7259	5.63	7.77	-2.782	-15.010	-17.811
6	60	24	2	0.2892	3.80	6.96	-10.777	-11.589	-16.852
7	90	8	6	0.8675	6.81	9.89	-1.234	-16.663	-19.903
8	90	16	2	0.3744	4.60	8.73	-8.533	-13.263	-18.819
9	90	24	4	0.5472	5.47	7.66	-5.237	-14.757	-17.680

3.1. Statistical Significance

The statistical significance of input factors on the performance measures of MRR, SR, and RLT has been studied with the help of the Minitab v17 tool. In accordance with analyzing statistical data of input factors correlated with output measures, the statistical method of ANOVA was employed to verify the adequacy of obtained results. Ninety-five percent of the confidence interval has been taken into account, meaning that the P-value of input factors must be less than 0.05 to significantly contribute to the selected response measure [35]. An ANOVA table for all output measures of MRR, SR, and RLT has been depicted in Table 3. Statistical analysis for all the output measures shows that the generated regression terms had a significant impact. It obviously revealed the suitability of the data. For single output measures, higher-F/lower-P numbers have identified that current was having a substantial effect on both MRR and SR, while T_{off} was the largest contributor in the case of RLT. In the case of the non-significance of input factors, T_{on} , T_{off} , and current did not have a meaningful contributor in MRR, SR, and RLT, respectively. Thus, all the input factors apart from Ton in the case of MRR; Toff in the case of SR; and current in RLT showed a significant contributing effect on the performance measure characteristics of the near-dry WEDM process. Insignificant error contributions and smaller standard deviations were recorded for performance measures. The competence of the suggested regression was determined through R^2 values. The coefficient of determinations (R^2) was observed to be nearly in unity with the values of 0.9655, 0.9552, and 0.9491 for MRR, SR, and RLT, respectively. R2 values close to unity for all output measures have shown the suitability of the obtained results. Thus, the results obtained from the statistical findings clearly show the present study's acceptability and fitness.

Source	DF	Adj. SS	Adj. MS	F-Value	p-Value	
MRR						
Regression	3	0.27066	0.09223	46.65	0.000	
Ton	1	0.00821	0.00821	4.25	0.094	
T_{off}	1	0.04847	0.04847	25.06	0.004	
Current	1	0.21397	0.21397	110.63	0.000	
Error	5	0.00967	0.00193			
Total	8	0.28033				
Standard devi	iation = 0.0439;	$R^2 = 0.9655; R^2$ ac	dj. = 0.9448.			
SR						
Regression	3	6.60960	2.20321	35.50	0.001	
Ton	1	1.12360	1.12360	18.10	0.008	
T_{off}	1	0.18530	0.18530	2.99	0.145	
Cürrent	1	5.30070	5.30070	85.41	0.000	
Error	5	0.31030	0.06206			
Total	8	6.91990				
Standard deviation = 0.2491 ; R ² = 0.9552 ; R ² adj. = 0.9283 .						
RLT						
Regression	3	7.66330	2.55443	31.09	0.001	
Ton	1	3.80170	3.80170	46.27	0.001	
T_{off}	1	3.84000	3.84000	46.74	0.001	
Cürrent	1	0.02160	0.02160	0.26	0.630	
Error	5	0.41082	0.08216			
Total	8					
Standard devi	iation = 0.2866;	$R^2 = 0.9491; R^2$ ad	dj. = 0.9186.			

Table 3. Statistical significance of output measures through ANOVA from regression analysis.

Residual plots substantiate the positive findings of the ANOVA results. ANOVA analysis can be considered to be valid and appropriate for the chosen model if certain

conditions are met [36]. Validation of residual plots is crucial for this purpose. Figure 2a–c displays the residual plots which contain the four plots for MRR, SR, and RLT, respectively. The residual plot for MRR is displayed in Figure 2a. The normality plot illustrates a linear growth. It implies that the model is appropriate. The second versus fit graphic has demonstrated that fits were completely random around the source. The histogram plot shows a bell-shaped curve representing the data needed for a strong ANOVA. The ANOVA data are confirmed by the versus order plot, which shows no specific trend [37]. The current study's four residual plots confirmed the ANOVA statistics for a more accurate forecast of results. The SR and RLT measurements were similar for all four residuals, as shown in Figure 2b,c, respectively. Thus, obtained results of residual plots for all performance measures imply good ANOVA results and satisfy the necessary condition for ANOVA.



Figure 2. Residual plots for (a) MRR, (b) SR, (c) RLT.

3.2. Effect of Near-Dry WEDM Variables on Output Measures

The effect of near-dry WEDM variables has been studied on output measures (MRR, SR, and RLT) through main effect plots. The statistical tool Minitab 17 was employed to plot the main effect plots for performance measures.

Figure 3 represents the effect of T_{on} on performance measures of MRR, SR, and RLT. It was discovered that (MRR, SR, and RLT) increased as T_{on} increased. During the machining, the substance quantity gets degraded owing to the formation of repeated sparks. With an increase in T_{on} , these outflows rise. The work material melts and vaporizes as a result of the increased thermal energy. Increased erosion from work materials occurs due to an increase in melting and vaporization [38]. This raises the machining zone's MRR. Due to the increase in T_{on} , these high-frequency sparks produce higher temperatures, which in turn cause numerous flaws on the machined surfaces [39]. Large and deep craters form on the work material as a result of an increased rate of erosion as T_{on} rises. The machining surface becomes rougher and depreciates as a result. SR increases when T_{on} increases.

More discharge energy is implied by a longer T_{on} , so it enhances the workpiece's melting rate. Consequently, more molten material is accessible for creating a thicker recast layer by recasting on the surface [40]. The typical RLT rises for a consistent peak current with a prolonged pulse-on-time. This is substantial because more heat is due to the longer pulse-on periods and the dielectric being more porous; more energy is unable to flush the extra molten metal away effectively because the flushing pressure is constant [28]. Longer T_{on} fundamentally leads to an increase in the penetration of electro-discharge energy into the surface that significantly lengthens the bigger area of the melting isothermals inside the workpiece and, as a result, creates a molten zone, which leads to an elevated RLT. The recast layer's thickness is increased, and thus it suggests an increased surface hardness, residual stress, and roughness.



Figure 3. Effect of T_{on} on MRR, SR, and RLT.

Figure 4 depicts the effect of T_{off} on the performance measure of MRR, SR, and RLT. With the increase in T_{off} , a consistent downward trend could be seen in all the responses (MRR, SR, and RLT). The increased value of T_{off} increases the gap between subsequent sparks. This adds to a decrease in the energy and number of active sparks. The thermal energy is further decreased by decreased discharge energy, and as a result, the work material's melting and vaporization rates decline [41]. In light of this, the elevated value of T_{off} reduces the MRR since the spark has decreased. Uniform erosion detracts from the workpiece as T_{off} rises. Additionally, there is more time to flush the molten waste materials off the surface of the machined workpiece. This results in a small crater, which improves the smoothness of the surface of the machined work material [42]. SR decreases when T_{off} increases. The recast layer thickness decreases when pulse-off time is prolonged. Due to the most effective flushing of the molten material away from the machined surface, the entire cycle time, which includes the non-sparking cycle, has effectively increased [43]. This suggests less melting and evaporation. This reduces the RLT of the machined zone.



Figure 4. Effect of T_{off} on MRR, SR, and RLT.

Figure 5 depicts the effect of current on the performance measure of MRR, SR, and RLT. MRR and SR were found to increase with the increase in the value of current. The energy of discharge increases with an increase in current. An increase in thermal energy melts and vaporizes the work material, while an increase in discharge energy strengthens the thermal energy even more [44]. Higher melting and vaporization cause more work material to erode. The MRR rises as a result. It can be observed that the value of RLT initially decreases with the current rise and then increases after the increased current value. This is because, at the higher current value, more molten metal gets deposited on the surface as it does not get sufficient time to flush away due to a higher amount of discharge energy [38]. As spark energy is inversely proportional to current and T_{on}, this was caused by the greater spark energy available for melting material from workpiece surfaces. High spark energy causes the plasma channel pressure to rise, producing an impulsive force and erratic surfaces [45]. This raises the machined zone's SR.



Figure 5. Effect of current on MRR, SR, and RLT.

3.3. Grey Relational Analysis

The GRA approach was employed to simultaneously optimize the selected output factors. Pursuant to this, GRA was used to create a single objective function from all the output factors. Taguchi's approach was coupled with the GRA technique. Individual objectives were converted into solitary functions through S/N ratios. Pursuant to this, MRR was assigned higher-the-better characteristics, and SR and RLT were assigned lower-the-better characteristics. Simultaneous optimization of output measures was attained through the below-mentioned steps:

1. Determination of S/N ratio

Experimental results of output factors need to be converted into unitless quantities. Pursuant to this, S/N ratios were calculated for individual output characteristics. As MRR belonged to the higher-the better measures, Equation (2) was used to determine the S/N ratio of MRR:

$$\frac{S}{N} \text{ratio} = -10 lg(1/n) \sum_{n=1}^{n} \left(\frac{1}{y_{ij}^2}\right)$$
(2)

where, i = 1, 2, ..., n; j = 1, 2, ..., k; n = number of repetitions; ij = output response values (i.e., MRR).

Equation (3) was employed for the S/N ratio of SR and RLT as both these output factors belonged to the lower-the-better characteristics.

$$\frac{S}{N} \text{ratio} = -10 lg(1/n) \sum_{n=1}^{n} \left(y_{ij}^2 \right)$$
(3)

Table 2 shows the obtained values of S/N ratios of all the output factors (MRR, SR, and RLT).

2. Normalization

The obtained values of S/N ratios were normalized in the domain of 0 to 1 for further processing [46]. Equation (4) was used for calculating the normalized value of MRR, while Equation (5) was used for both SR and RLT.

$$A_{1i}^{*} = \frac{A_{1i} - minA_{1i}}{maxA_{1i} - minA_{1i}}$$
(4)

$$A_{2i}^{*} = \frac{maxA_{2i} - A_{2i}}{maxA_{2i} - minA_{2i}},$$
(5)

here, A_i^* represents the normalized values of output factors; *i* represents number of experimental items, and * shows the normalization. Least and highest values were shown by $minA_{1i}$ and $maxA_{1i}$, respectively. Table 4 has shown the calculated normalized values of each output measure.

 Table 4. Obtained values from normalization, GRC, and GRG.

Sr No	Normalization		Deviations			GRC			CBC	
5r. 100.	MRR	SR	RLT	MRR	SR	RLT	MRR	SR	RLT	GIG
1	0.295	0.050	0.644	0.705	0.050	0.644	0.415	0.909	0.437	0.587
2	0.609	0.424	0.260	0.391	0.424	0.260	0.561	0.541	0.658	0.587
3	0.669	0.638	0.000	0.331	0.638	0.000	0.601	0.440	1.000	0.680
4	0.819	0.508	0.637	0.181	0.508	0.637	0.735	0.496	0.440	0.557
5	0.838	0.674	0.557	0.162	0.674	0.557	0.755	0.426	0.473	0.551
6	0.000	0.000	0.354	1.000	0.000	0.354	0.333	1.000	0.586	0.640
7	1.000	1.000	1.000	0.000	1.000	1.000	1.000	0.333	0.333	0.556
8	0.235	0.330	0.770	0.765	0.330	0.770	0.395	0.602	0.394	0.464
9	0.581	0.624	0.529	0.419	0.624	0.529	0.544	0.445	0.486	0.491

3. Deviation

Equation (6) was employed to determine deviation [46].

$$\Delta_{0i}(x) = |A_0^*(\mathbf{m}) - A_1^*(\mathbf{m})|$$
(6)

here, $\Delta_{0i}(x)$, $A_0^*(m)$, and $A_1^*(m)$ represent the deviation, reference, and normalized sequences, respectively. Additionally, *x* represents response measures, i.e., MRR, SR, and RLT, while m represents the number of trials, i.e., 1, 2, 3 . . . , 9.

4. Grey Relational Coefficient (GRC)

Equation (7) was used to determine the GRC of response measures. Table 4 depicts the GRC values of all the response measures.

$$GRC = \frac{\Delta min + \xi \Delta max}{\Delta_{0x}i + \xi \Delta max}$$
(7)

where ξ is the distinguishing coefficient whose value lies in between 0 and 1. The present study's value is usually taken as 0.5 [47]. Additionally, Δ_{min} and Δ_{max} represent the smallest and largest value in the overall sequence for all the experiments from both MRR and SR.

5. Grey Relational Grade (GRG)

GRG is nothing but the average value of all the GRCs of the studied response measures. Equation (8) was used to determine the GRG.

$$GRG_i = \frac{1}{3} \sum_{j=1}^{3} GRC(m)$$
 (8)

GRG values were represented in Table 4. It can be observed that experimental trial 3 has shown the largest value of GRG. This implies that experimental trial 3 showed the best parametric settings for the selected multiple responses from the nine experimental trials. Experimental trial 3 was trailed by a further trial number, 6, which has shown 2nd best parametric settings from the nine trials. However, it may be possible to have a more significant parametric settings to achieve all the performance measures. Pursuant to this, means of GRG levels were determined for all the input factors as shown in Table 5.

Table 5. Factor response table of GRG.

Levels/Control Factors	Ton	T _{off}	Current
1	0.6180	0.5663	0.5634
2	0.5852	0.5339	0.5957
3	0.5034	0.6038	0.5449

The means of GRG shown in Table 5 represent the average value obtained for each level of input factor. In the present study, three input factors at three levels were studied by using Taguchi's L9 approach. For the present work, T_{on} was varied at three different levels of 30 µs, 60 µs, and 90 µs and each level was changed for the three experimental trials. T_{off} was varied at three levels of 8 µs, 16 µs, and 24 µs and each level was changed for the three experimental trials. Current was varied at three different levels of 2 A, 4 A, and 6 A and each level was changed for three experimental trials. Thus, the GRG values represented in Table 5 depicted that the highest GRG was obtained at level 1 of T_{on} , level 3 of T_{off} , and level 2 of current. This shows that the optimal parametric settings for simultaneous performance measures of MRR, SR, and RLT were found to be at T_{on} of 30 µs, T_{off} of 24 µs, and current of 4 A.

3.4. Confirmation Trial

A validation trial was conducted at the obtained parametric settings to check the GRA's adequacy. Equation (9) was used to determine the predicted values of response measures at the optimal parametric settings at T_{on} of 30 µs, T_{off} of 24 µs, and current of 4 A.

$$\overline{y}_{1(predict)} = \overline{y}_{1(A1)} + \overline{y}_{1(B3)} + \overline{y}_{1(C2)} - 2\overline{y}_{1(avg)}$$
(9)

where $\overline{y}_{1(avg)}$ is the average value of the respective response measures (MRR, SR, RLT); $\overline{y}_{1(A1)}$, $\overline{y}_{1(B3)}$, $\overline{y}_{1(C2)}$ depicted the average values of response measures (MRR/SR/RLT) for the input factor levels of T_{on} (level 1), T_{off} (level 3), and current (level 2), respectively. Table 6 shows the obtained results for both the predicted and actual confirmatory trials. The minor acceptable deviation was recorded among the anticipated and recorded values. This clearly reveals the acceptability of the integrated approach of the Taguchi–Grey method.

Table 6. Results of confirmatory trials.

Response Measure	Predicted Results	Confirmatory Results	% Deviation
MRR	0.6142	0.6273	2.08
SR	5.53	5.46	1.28
RLT	5.96	6.11	2.45

3.5. Machined Surface Morphology

Understanding the importance of design variables and the machining process depends on the morphology of the machined surface. Optimized GRA method parameters were chosen to analyze the surface morphology of both the NDWEDM and wet-WEDM processes. The SEM images of the machined surface obtained from the wet-WEDM and NDWEDM processes are shown in Figure 6a,b, respectively. Figure 6a demonstrates the prominent presence of surface flaws such as globules and the deposition of hardened material, as well as micro-voids and micro cracks. This resulted from the wet-WEDM method's significant thermal energy output. A higher temperature is produced at the inter-electrode gap (IEG) as a result of the high thermal energy being generated, which increases the spark's intensity [48]. During the erosion of the molten material from the work surface, the molten material breaks into tiny droplets. Some of these molten droplets flushed out from the IGP, and a few droplets get re-deposited on the machined surface [49]. The molten droplets in the re-deposition are termed as globules. More material is subsequently evaporated as a result, leading to high surface deviations such as micro-voids, the deposit of solidified material, and micro-cracks. The machined surface created utilizing the NDWEDM method, as shown in Figure 6b, on the other hand, shows lower surface deviations. The NDWEDM process makes use of a mixture of compressed air and dielectric fluid, the additional cooling effect and lower current density resulting in the fast cooling of molten droplets [49]. This in turn enhances their flushing from IGP. Thus, it can be concluded that a provision of an air-water mixture enhances the heat liberation from molten material. This leads to the reduction in the globules' formation in the shape of tiny debris on the machined surface during the NDWEDM process. As a result, tiny shallow craters begin to form, improving the surface quality by fewer surface flaws, including micro-voids, the deposition of solidified material, and micro-cracks [50]. Therefore, compared to the wet-WEDM process, low viscosity, lower heat energy at IEG, and improved flushing of eroded material for an air-mist mixture led to better surface shape and better surface quality of Nitinol SMA.



Figure 6. Surface morphology for (a) wet-WEDM, and (b) near-dry WEDM at optimized parameters.

4. Conclusions

In the present study, a near-dry WEDM process using air as a compressed gas and a minimum quantity of dielectric fluid has been used for the machining of Nitinol SMA. The studied literature has identified input factors of T_{on} , T_{off} , and current and output factors of MRR, SR, and RLT. The obtained results have drawn the following conclusions:

- The statistical significance of input factors through ANOVA techniques has shown that all the output measures have a significant influence on the generated regression terms. For single output measures, higher-F/lower-P numbers have identified that current was having a substantial effect on both MRR and SR, while, T_{off} was the largest contributor in the case of RLT.
- R2 values close to unity for all output measures have shown the suitability of the
 obtained results. Thus, the results obtained from the statistical findings clearly show
 the present study's acceptability and fitness. The obtained results of residual plots for
 all performance measures implied good ANOVA results.
- The effect of near-dry WEDM variables was studied on output measures through main effect plots. It was found to have a contradictory nature of input factors to attain the desired levels of MRR, SR, and RLT.
- Grey relational analysis (GRA) has been employed to attain optimal parametric settings of multiple performance measures. GRA technique for the optimal parametric settings of simultaneous performance measures of MRR, SR, and RLT was found to be at T_{on} of 30 μs, T_{off} of 24 μs, and current of 4 A. The optimal parametric settings have resulted in an MRR value of 0.6273 mm³/sec, SR of 5.46 μm, and RLT of 6.11 μm.
- Validation trials were conducted to check the adequacy of the GRA technique. The minor acceptable deviation was recorded among the anticipated and recorded values. This clearly revealed the acceptability of the integrated approach of the Taguchi–Grey method.
- The surface morphology results obtained through SEM have shown that the near-dry WEDM process of an air-mist mixture led to a better surface quality and superior finish as compared to the wet-WEDM process of Nitinol SMA.
- The author considers that the present study will be beneficial for users working in WEDM and the near-dry WEDM process for hard machining materials.

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Nomenclature

ANOVA	Analysis of variance
DOE	Design of experiments
EDM	Electrical discharge machining
FESEM	Field emission scanning electron microscope
GRA	Grey relational analysis
IEG	Inter-electrode gap
MRR	Material removal rate (mm ³ /sec)
NDEDM	Near-dry electrical discharge machining
NDWEDM	Near-dry wire electrical discharge machining
RSM	Response surface methodology
SEM	Scanning electron microscope
SMA	Shape memory alloy
SMAs	Shape memory alloys
SME	Shape memory effect
SR	Surface roughness (µm)
Ton	Pulse-on-time (µs)
T _{off}	Pulse-off-time (µs)
t	Time in seconds
RLT	Recast layer thickness
WEDM	Wire electric discharge machine
ρ	Density in g/cm ³

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