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ANALYSIS AND OPTIMISATION OF PERFORMANCES OF ELECTRO DISCHARGE MACHINING OF SHAPE MEMORY ALLOY (NITINOL)

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ABSTRACT

A conventional machining has the limitation for machining advanced materials since it requires that the cutting tool material is harder than the work piece material. There is the need of use of non-conventional machining process such as electro-discharge machining (EDM) process for machining of shape memory alloy (NiTinol). A very few investigations have been documented to analyse the machining characteristics of EDM process during machining of NiTinol. In this investigation an analysis has been made on the effects of various process parameters such as polarity, peak current, pulse on-time, spark time etc. on MRR and Taper angle during drilling on shape memory alloy such as Nitinol by EDM process based on L18 OA of Taguchi method. The polarity and pulse on-time are significantly most influential process parameters. Maximum MRR and minimum taper angle are found at 12A/20 ・ s/6s and 12A/30 ・ s/4s respectively.

Keywords: EDM, MRR, Taper angle, NiTinol

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1. Introduction

Machining of difficult-to-machine materials such as ceramics, various alloys of metals poses a new challenge in different fields. The ceramics are employed in the machine tool, aerospace, automotive, electrical and electronics sectors. Conventional machining processes like turning, milling grinding does not hold good to machine those difficult to machine materials. Ceramics have high corrosion resistance, high compressive strength, good creep resistance, high temperature resistance, high hardness and strength characteristics at elevated temperatures, a stronger electro-magnetic response, high wear resistance, low friction, high refractoriness, etc.

Electro-discharge machining (EDM) process has been widely explored in various research domains, its application for machining on electrically non-conducting materials remains limited. There is a strong need of in-depth studies and experimental investigations into the process, particularly focusing on electro-discharge drilling of different advanced engineering materials. Significant research efforts and technical advancements are required to enhance this technology, widely accepted in modern manufacturing industries for machining of advanced engineering materials.

Till date several researchers have investigated on electro-discharge machining for different materials especially electrically conducting materials. Darji *et al*. [1] using the Taguchi methodology, investigated the machining properties of Hastelloy C276 with a 0.5 mm graphite rod as electrode by conducting tests and research for altering machining parameters such as polarity, peak current, electrode rotational speed, and pulse on time. Yadav *et al.* [2] looked into how electrical discharge machining (EDM) produced strong temperature gradients at the gap, which led to significant localised thermal stresses in a tiny heat-affected zone. Microcracks, a reduction in strength and fatigue life, and even catastrophic failure could result from these thermal stresses. Keskin *et al*. [3] found that, surface roughness was the most crucial performance metric in EDM, outperforming other performance metrics including material removal rate (MRR) and tool wear rate (TWR). In order to identify the parameters influencing surface roughness, tests were conducted in this study. Pachaury and Tandon [4] investigated on EDM to machine different ceramic materials such as ZrO_2, Al_2O_3, Si_3N_4, SiC, and their composites. Pei *et al*. [5] found that tool wear in electrical discharge machining (EDM) is an unavoidable occurrence that negatively impacts the geometrical correctness of machined features. Murray *et al*. [6] documented that during electrical discharge machining (EDM); ablated work piece material was rapidly solidified upon ejection into the dielectric and thought not to become reattached to the electrode surfaces. Weinterz and Petzoldt [7], the machinability constraints arises with the use of conventional machines while machining of NiTi alloys such as wear of tool, formation of adverse chips, burr formation after machining and grinding. Nonconventional machining techniques like electrical discharge machining (EDM) and wire-EDM (WEDM) can be used to correctly machine them in order to solve such issues. According to M. Manjaiah [8], traditional SMA machining has drawbacks including a high working temperature, poor accuracy, and high expense.

From the literature review it is evident that there are lot of aspects need to be investigated to control the machining parameters so that the EDM process shall be effectively utilised to machine advanced engineering materials such as shape memory alloy (NiTinol) at desired machining rate with adequate dimensional accuracy. In this research paper the influences of various process parameters such as polarity, peak current, pulse on-time, spark time etc. on MRR and Taper angle have been investigated during drilling on shape memory alloy such as Nitinol by electro-discharge machining (EDM) process based on Taguchi method. Also, the optimal parametric combinations of EDM process for maximum MRR and minimum taper angle has been search out based on S/N ratio of Taguchi method during drilling operation on Nitinol.

2. Materials and methods

Experiments have been carried out using S-40 ZNC Die-Sinking EDM set-up equipped with SRP Control Panel made by Electronica Machine Tools Private Limited, Pune. The experimental set-up consists of three sub-systems like main machining chamber, power supply and control unit and dielectric supply unit. The photographic view of EDM set-up is shown in Fig.1. The pulsed D.C. power was supplied between the tool and workpiece and it provides voltage ranging from 0 to 60 V. A copper tool of diameter 2mm was chosen for experimentation and connected to the negative terminal of power supply.

Fig. 1 Photographic view of S-40 ZNC Die-Sinking EDM Machine

The experimental scheme has been designed in such a way that experiments can be carried out for parametric analysis on EDM performances during machining of shape memory alloy. In the present set of experimental study, EDMing operation was performed on work sample NiTinol. The straight and reverse polarity methodology selected to carry out the optimization of variable control parameters of the machining operation of NiTinol. These properties make NiTinol an exceptional material for a wide range of applications, particularly in the medical field, aerospace, robotics. Its unique combination of shape memory, super-plasticity and biocompatibility distinguishes it from other materials. The material NiTinol used for the experimentation chemically consists of 49.1% Ni and 50.9% Ti. The physical properties of NiTinol have been listed in the Table 1.

Table1: Physical and mechanical Properties of NiTinol

Melting Temperature	1240 - 1310 °C
Resistivity (high temp. state)	82 μΩ-cm
Resistivity (low temp. state)	76 μΩ-cm

Thermal Conductivity	0.1W/cm/°C
Heat Capacity	0.077 cal/gm-°C
Latent Heat	5.78 cal/gm
Tensile Strength	Austenite: 195-690 MPa Martensite: 70 -140 MPa
Young's Modulus	Austenite: 83 GPa Martensite: 28-41GPa
Density	6.45 gm/cm^3

The selection of process parameters in EDM process is crucial for achieving desired outcomes and optimizing the machining performance. A series of trial experiments are conducted to arrive at an understanding to observe all the variables, responses, and their relationship for the drilling operation. It was found that the most influencing process parameters in EDM were peak current, pulse on time and sparking time. The present research work attempts to make investigation on EDM characteristics such as material removal rate (MRR), taper angle during machining of NiTinol. During machining peak current, pulse on time and sparking time will be considered as the process parameters during experimentation.

Selecting a copper electrode for EDM machining on NiTinol involves considering various factors to optimize the machining performance. Copper is a popular choice due to its advantageous properties such as electrical conductivity, thermal conductivity, wear resistance etc. the photographic view of the tool is shown in the Fig. 2 below. Selecting the right dielectric fluid is crucial for optimizing the EDM machining process of NiTinol. EDM oil is commonly used as a dielectric fluid due to its beneficial properties such as electrical insulation and cooling effect. To assess the effect of each machining parameter on the process and correlate between different process parameters and machining performance characteristics L_{18} orthogonal array of Taguchi approach was used. In this present study the levels of process parameters have been shown in Table 2. The matrix form of these arrays is shown in Table 3, where 1, 2, 3, 4 in the table represents the level of each parameter.

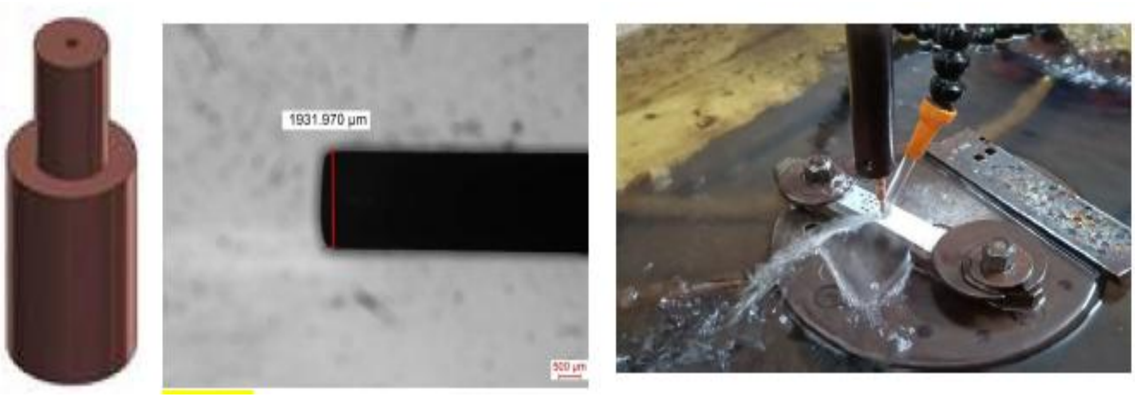


Fig. 2 Photographic and microscopic images of tool-electrode

Table 2. Process parameters and their levels

Parameters	Symbols	Levels		
		1	2	3
Polarity		+ve	-ve	
Peak current (A)	I_p	6	9	12
Pulse On-time (µs)	T_{ON}	10	20	30
Spark time (µs)	T_w	2	4	6

Here, '+ve' indicates Straight polarity when workpiece is connected with positive terminal of power supply and tool is connected with negative terminal and '-ve' indicates reverse polarity when workpiece is connected with negative terminal of power supply and tool is connected with positive terminal.

Table 3. Combinations of control parameters based on L_{18} Orthogonal array

Expt. No.	Col. No. & Factor assignment				Actual values of process parameters			
	1	2	3	4	Polarity	Peak current (A)	Pulse On-time (µs)	Spark time (µs)
1.	*1*	*1*	*1*	*1*	+	6	10	2
2.	*1*	*1*	*2*	*2*	+	6	20	4

3.	1	1	3	3	+	6	30	6
4.	1	2	1	1	+	9	10	2
5.	1	2	2	2	+	9	20	4
6.	1	2	3	3	+	9	30	6
7.	1	3	1	2	+	12	10	4
8.	1	3	2	3	+	12	20	6
9.	1	3	3	1	+	12	30	2
10.	2	1	1	3	-	6	10	6
11.	2	1	2	1	-	6	20	2
12.	2	1	3	2	-	6	30	4
13.	2	2	1	2	-	9	10	4
14.	2	2	2	3	-	9	20	6
15.	2	2	3	1	-	9	30	2
16.	2	3	1	3	-	12	10	6
17.	2	3	2	1	-	12	20	2
18.	2	3	3	2	-	12	30	4

In order to analyse the results, the Taguchi method uses a statistical measure of performance called signal-to- noise (S/N) ratio. The S/N ratio takes both the mean and the variability into account. The S/N ratio equation depends on the criterion for the quality characteristic to be optimised. S/N ratio is a mathematically transformed form for quality/ performance characteristic, the maximization of which minimizes quality loss and also improves statistically the additivity of control factor effects.

From the each experimental result S/N value can be calculated as follows:

For the ‘larger-the-better’ type problem

$$\eta = -10 log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \tag{1}$$

For ‘smaller-the-better’ type problem

$$\eta = -10 log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \tag{2}$$

The experimentations have been performed three times at each parametric combination and the average value of machining criteria has been utilised for statistical analyses. The diameter of machined micro-hole has been measured with the help of optical Olympus measuring microscope (LC 0.5 m). Material removal rate has been calculated by weight difference method and measured with the help of Metler Toledo weighing machine (LC 1×10^{-5} g). MRR and taper angle of holes have been calculated using the following Eqs. 3 and 4 and as per following Fig. 3.

$$MRR = \Pi \left[\left((D_{en} + D_{ex})^2 L/16\right)\right] \quad (3)$$

$$\text{Taper angle} = \tan^{-1}\left[(D_{en} - D_{ex})/2\,L\right] \quad (4)$$

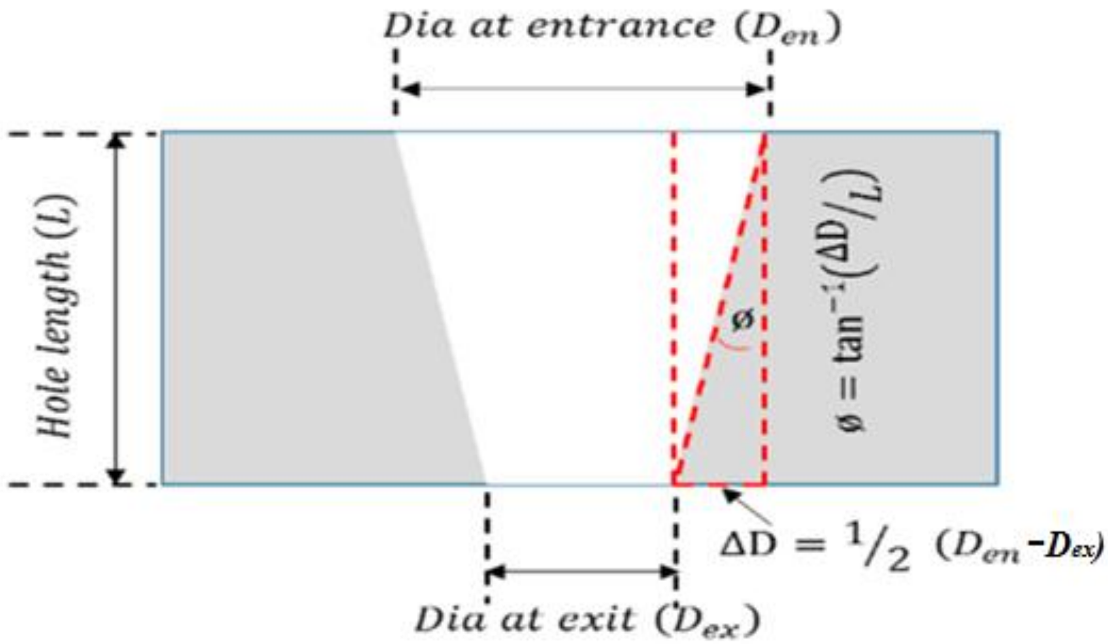


Fig. 3 Cross-section of a hole

3. RESULTS AND DISCUSSION

3.1 Experimental Results

A total of 18 experiments have been carried out. The results and the discussion section aim to analyse and interpret the data collected during the experiments and provide a comprehensive discussion of the outcomes. It allows for a deeper understanding of the effects of various parameters and their impact on the machining performance. The main objective of this experiment is to get maximum value of MRR with the "Larger is better" quality type problem for maximizing the MRR and Eq. 1 was utilized to get signal to noise (S/N ratio) whereas for "smaller the better" type responses i.e. taper angle Eq. 2 was used. The average values of experimental results and corresponding S/N ratios of various performance characteristics have been listed in Table 4. The photographic view of workpiece NiTinol has been depicted the following Fig. 4.

Table 4: Experimental Results Based on Taguchi Method and corresponding S/N Ratios for MRR and Taper angle

Expt. No.	Experimental results			S/N Ratio (dB)	
	Machining Time (s)	MRR (mm^3/s)	Taper Angle (rad)	For MRR	For Taper angle
1	164.49	0.0042322	1.145141	-47.46867634	0.27105
2	92.97	0.0106231	0.872813	-39.47497461	-0.27207
3	142.96	0.0070242	0.833571	-43.06806263	-0.36407
4	224.99	0.0036711	1.071378	-48.7040757	0.13789
5	79.47	0.0236991	0.944929	-32.50536293	-0.11329
6	58.49	0.032551	0.945055	-29.7487133	-0.11324
7	199.09	0.0099302	0.888063	-40.06084009	-0.23742
8	86.02	0.0228584	0.90822	-32.81908344	-0.19253
9	53.26	0.0359294	0.888533	-28.8910007	-0.23637
10	85.4	0.0032674	1.335153	-49.71595391	0.57809
11	94.7	0.0047626	1.364105	-46.44311785	0.62099
12	163.34	0.0032074	1.35329	-49.8769375	0.60508
13	94.81	0.0037625	1.285955	-48.49046983	0.50300
14	74.82	0.0043095	1.346512	-47.3114623	0.59503
15	164.34	0.0023822	1.357973	-52.46043559	0.61199
16	97.86	0.0047116	1.364127	-46.53663174	0.62103
17	173.96	0.0025917	1.366748	-51.72830543	0.62487
18	136.04	0.0042322	1.311217	-47.46867634	0.54191

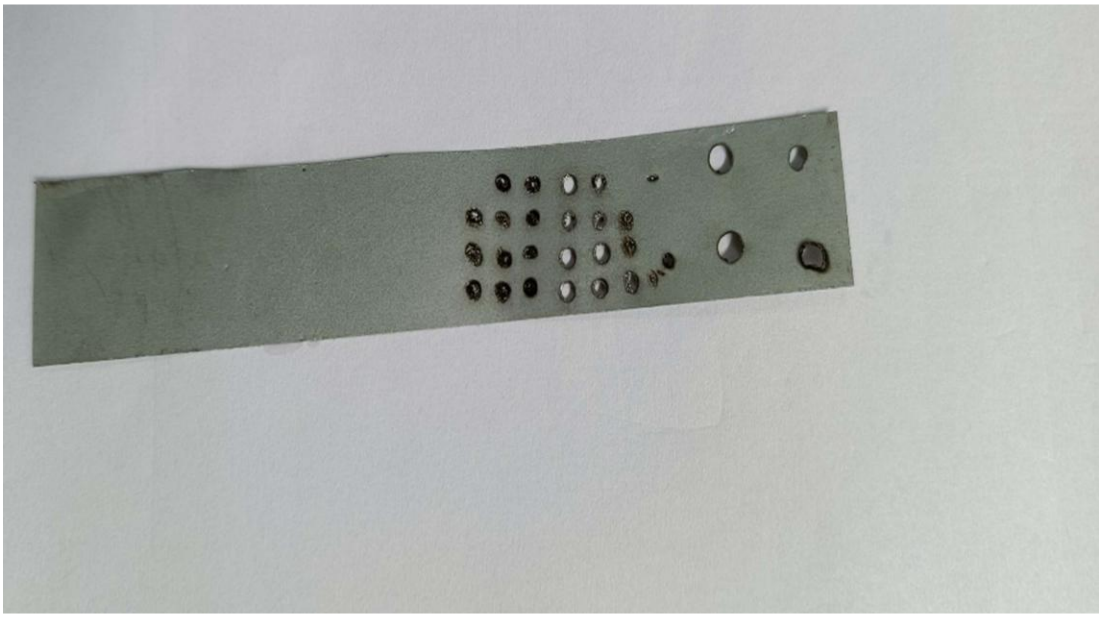


Fig 4 Workpiece (NiTinol) after Machining

3.2 Analysis on the effects of process parameters for different performance Characteristics

In robust design, Taguchi philosophy of orthogonal arrays determines the effects of various parameters efficiently. The analysis of the experimental results has been carried out based on the values of signal to noise (S/N) ratios.

3.2.1 Analysis on the effects of process parameters for MRR

The S/N ratio of graphs as shown in the Fig. 5 represents the variation of average S/N ratio at different level of machining parameters. According to the "Larger is better" principle the maximum value of S/N ratio refers to the Maximum MRR. In straight polarity MRR is found more compared to reverse polarity. The microscopic views of hole at different polarities are shown in the Fig. 6. Peak current increases the material removal rate because it produces more intense sparks that erode the material faster. However, it also worsens surface roughness due to deeper and more irregular craters, increases electrode wear, and can cause more thermal damage to the workpiece, potentially leading to micro-cracks or a heat-affected zone. Longer pulse on time also increases the material removal rate as more energy is input per pulse, leading to more material being eroded. However, it can also increase surface roughness due to larger craters on the workpiece surface, enlarge the heat-affected zone, and result in a thicker recast layer that may need additional processing to remove. Sparking time refers to the actual duration of the spark occurrence, related to the duty cycle of the EDM process. Higher sparking time means more frequent discharges, which increases the material removal rate. However, it can degrade surface integrity due to more consistent thermal cycling, potentially causing more thermal stresses and defects. It also accelerates electrode wear and can sometimes lead to unstable machining conditions like arcing or short-circuiting, which can damage both the workpiece and the electrode.

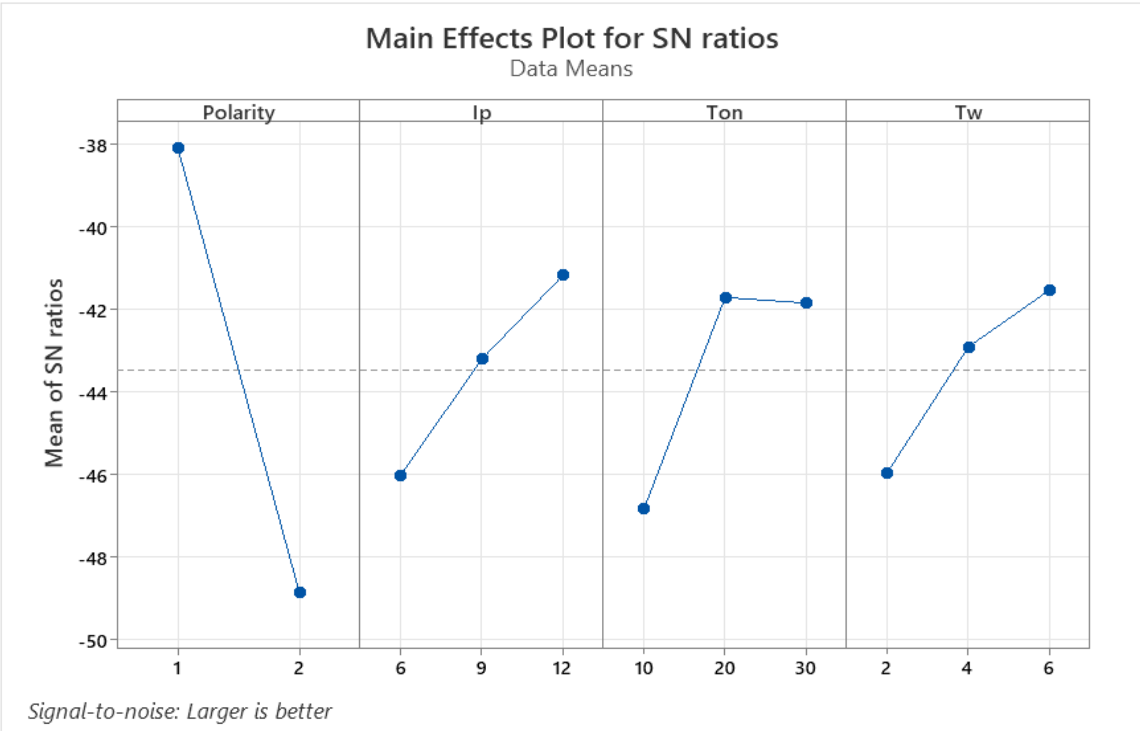
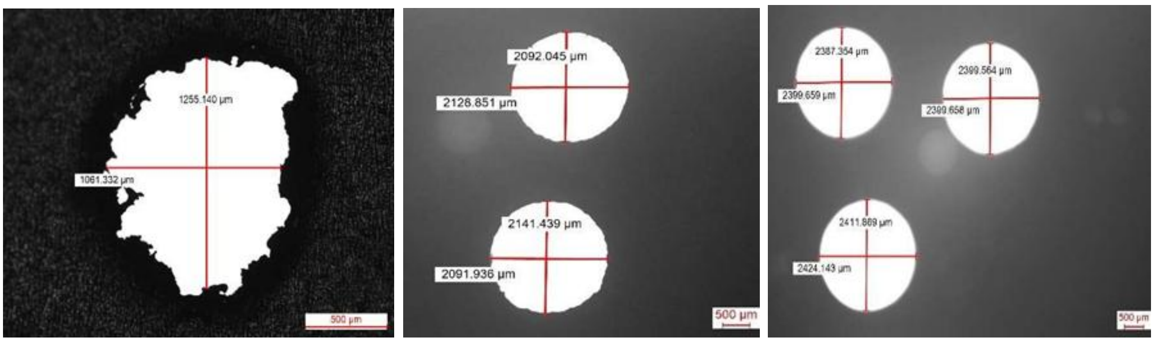
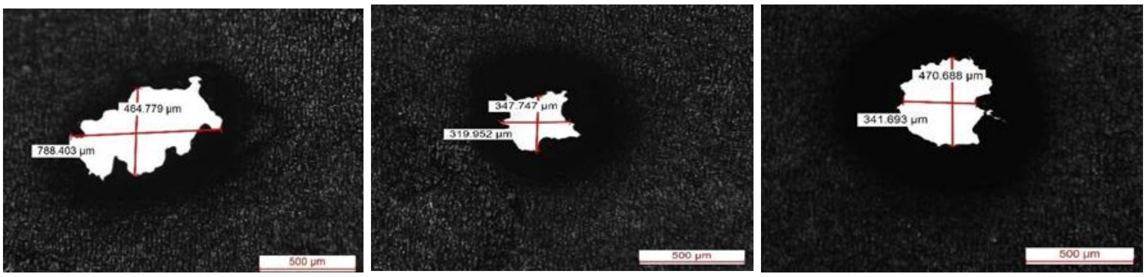


Fig. 5 Effects of process parameters on MRR



(a) Straight Polarity



(b) Reverse Polarity

Fig 6. Microscopic views of NiTinol after machining at 12A/20μs/6s

3.2.2 Effect of Different Process Parameters on Taper angle

The effects of different process parameters on Taper angle have been analysed based on S/N ratios and exhibited in the Fig. 7. The S/N ratio of graphs as shown in the figure represents the variation of average S/N ratio at different level of machining parameters. According to the "smaller is better" principle the maximum value of S/N ratio refers to the minimum Taper Angle. In straight polarity MRR is found more compared to reverse polarity. Peak current increases taper angle increase. The possible reason is that the sparking intensity increases with increase of peak current. Longer pulse on time also increases the material removal rate as more energy is input per pulse, which increases the material removal rate as well as taper angle. Larger sparking time means more frequent discharges. But at 6s of sparking time there may be a chance deposition of molten metal on machining zone due to improper flushing.

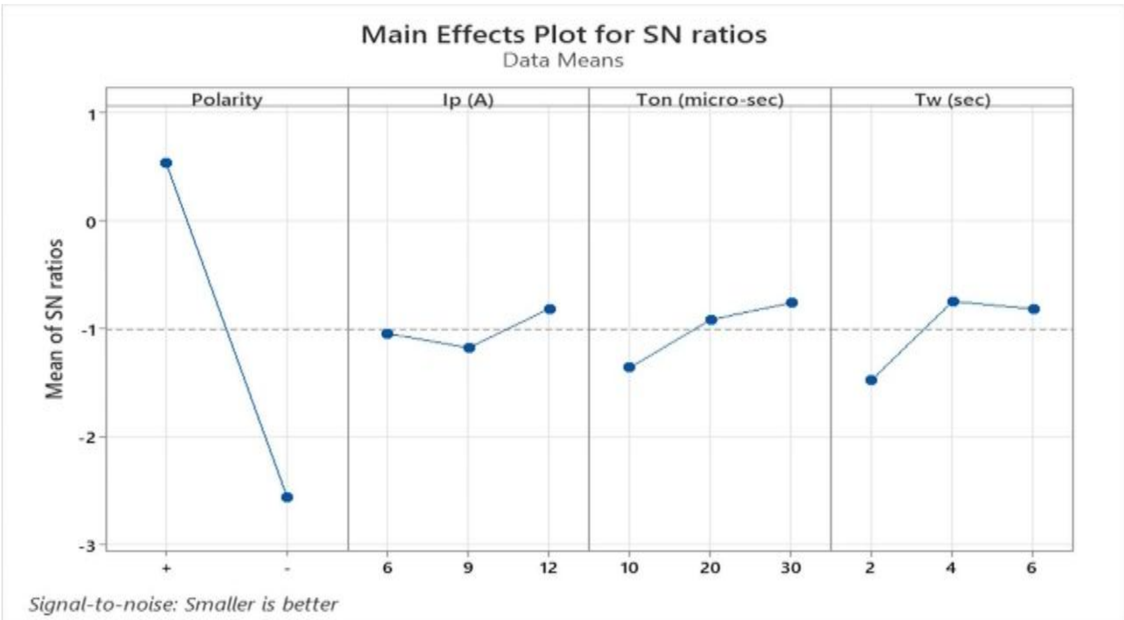


Fig. 7 Effects of process parameters on Taper Angle

3.3 Analysis of Variance (ANOVA) test for MRR and Taper angle

The Analysis of Variance (ANOVA) was conducted to assess the contributions of various parameters to Material Removal Rate (MRR). The results are summarized in the Table 5. Polarity exhibits a significant influence on MRR, with a percentage contribution of 81.67%. This indicates that polarity has a substantial impact on material removal efficiency. Ip demonstrates a moderate effect on MRR, contributing 5.53% to the variance observed. Although its contribution is relatively lower compared to Polarity, it still plays a discernible role in determining MRR. Ton shows a noteworthy influence on MRR, contributing 8.01% to the overall variance. This suggests that adjusting the on-time duration can significantly affect material removal efficiency. Tw contributes 4.79% to the variance in MRR. While its influence is not as pronounced as other parameters, it still contributes to the variability observed in material removal. According to ANOVA test polarity and pulse on-time are significantly most influential process parameters.

Table 5 Analysis of Variance (ANOVA) test for MRR

Source	DOF	Seq SS	Adj MS	F-ratio	Percentage Contribution
Polarity	1	521.18	521.18	20.81	81.67
Ip	2	70.58	35.29	1.41	5.53
Ton	2	102.03	51.02	2.04	8.01
Tw	2	61.28	30.64	1.22	4.79
Error	10	250.53	25.05		
Total	17	1005.61			

The Analysis of Variance (ANOVA) was carried out to assess the contributions of various parameters to taper angle. Polarity exhibits a significant influence on Taper angle, with a percentage contribution of 96.12%. This indicates that polarity has a substantial impact on material removal efficiency. Ip demonstrates a very low effect on Taper angle contributing 0.45% to the variance observed. Although its contribution is relatively lower compared to Polarity, it still plays a distinct role in determining taper angle. Ton shows a noteworthy influence on Taper angle, contributing 1.29% to the overall variance. Tw contributes 2.14% to the variance in MRR. While its influence is not as pronounced as other parameters, it still contributes to the variability observed in material removal. The results are summarized in the Table 6.

Table 6 Analysis of Variance (ANOVA) test for Taper angle

Source	DOF	Seq SS	Adj MS	F-ratio	Percentage Contribution
Polarity	1	43.231	43.231	139.99	96.12
Ip	2	0.4027	0.20135	0.65	0.45
Ton	2	1.1589	0.5795	1.88	1.29
Tw	2	1.9245	0.9622	3.12	2.14
Error	10	3.0876	0.3088		
Total	17	49.7867			

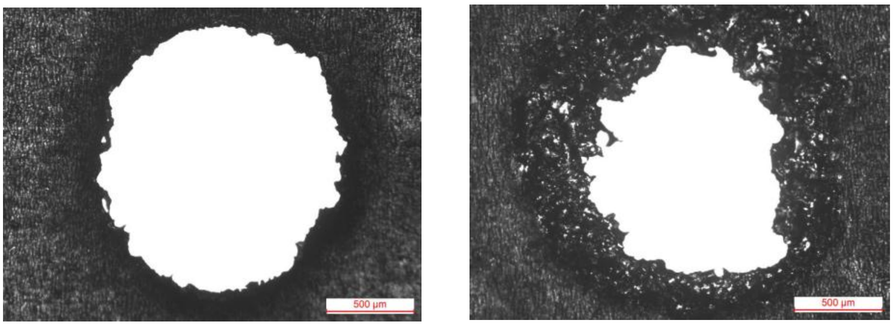
3.4 Determination of optimal parametric combination

The effects of different process parameters on Nitinol machining performance have been analysed and discuss based on the S/N ratio curves previously. At the same time there is a requirement of determining the optimal parametric condition, which can reduce the time as well as cost of machining. From the analyses of the S/N ratio curves the best combinations for the machining for different optimal requirements have been obtained and shown in the Table 7.

Table 7. Optimal parametric combination for maximum MRR and minimum Taper angle

parameters	Levels of process parameters	
	For maximum MRR	For minimum Taper angle
Polarity	Straight	Straight
Peak current (Ip)	12 A	12 A
Pulse On-time (Ton)	20 μs	30 μs
Spark Time (Tw)	6 s	4 s

Fig. 8 shows a hole obtained at straight polarity (+),with peak current (Ip) of 12 A, pulse on time (Ton) of 30 □s, and sparking time (Tw) of 4 second.



(a) Entry of hole **(b) Exit of hole**

Fig. 8 Microscopic views of hole with Straight polarity at 12A/30□s/4s

4. CONCLUSIONS

(i) In straight polarity MRR is found more compared to reverse polarity. Peak current increases the material removal rate because it produces more intense sparks that erode the material faster. MRR increase with pulse on-time and sparking time.

(ii) In straight polarity MRR is found more compared to reverse polarity. Peak current increases taper angle increase. Peak current increases taper angle increase. Sparking also increase taper angle.

(iii) According to ANOVA test polarity and pulse on-time are significantly most influential process parameters.

(iv) Maximum MRR and minimum taper angle are found at 12A/20□s/6s and 12A/30□s/4s respectively.

These experimental studies have been done for some particular levels of parameters without considering interactive effects. As well as, it is not sufficient to know the effect of parameters at any intermediate levels of various process parameters. Therefore, it is further needed to establish empirical relationships between significant parameters and machining criteria, which can help to analyse the interactive effect of various process parameters and find out the optimal settings at any intermediate levels of various process parameters during drilling operation on NiTinol utilising` EDM process.

However, the research outcomes will provide valuable guidance to the applied researchers and manufacturing scientists for setting up unique platform for machining advanced engineering materials such as shape memory alloy NiTinol with desired machining rate and accuracy.

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