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Wire Spark Erosion Machining of Ni rich NiTi Shape Memory Alloy for Bio-Medical Applications

Neeraj Sharma[a], Kapil Gupta[a*]

[a]*Department of Mechanical and Industrial Engineering Technology, University of Johannesburg, Doornfontein Campus, Johannesburg, Republic of South Africa*

Abstract

The application of NiTi shape memory alloys are growing day by day in biomedical industry. These materials present inherent problems when undergoing conventional machining processes during manufacture of bioimplants. Conventional machining processes require high consumption of energy and resources, and assistance of post processing operations to make high quality implants of shape memory alloys. Unlike conventional methods, nonconventional methods are capable to eliminate the need for post processing amongst other advantages and thus prove to be the most economic means of producing biomedical implants. Wire spark erosion machining (also known as Wire Electro Discharge machining i.e. Wire-EDM) is one such nonconventional machining process that has been explored for the machining of biomedical implants by Ni rich NiTi. The present study aims to analyze and optimize the machinability of $Ni_{55.8}Ti$ shape memory alloy during wire electric discharge machining for biomedical applications. The L_{16} Orthogonal array using Taguchi design of experiments has been employed for this experimental study. The variable input parameters are namely pulse on time, pulse off time, servo voltage and wire feed rate. Machining at optimum parameters produced good surface finish, high material removal rate and excellent surface integrity. In this paper, specifically, the effect of the aforementioned Wire-EDM parameters on cutting rate, process optimization for the highest cutting rate, and surface roughness obtained at optimum parameters are reported. The outcomes encourage exploring wire spark erosion machining of other shape memory alloys for different scientific and industrial applications.

Keywords: Biomedical; Machinability; NiTi; Surface Integrity; Productivity; WEDM

*Corresponding Author
Email: kgupta@uj.ac.za

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1. Introduction

Shape memory alloys are ‘smart materials’ due to their special properties such as pseudoelasticity, shape memory effects, biocompatibility, robustness, and light wetness etc. [1, 2]. Nickel titanium (NiTi) shape memory alloy is prominently used in biomedical, industrial and aerospace applications. Ni rich NiTi is mainly used in biomedical applications such as dental and orthopedic implants, surgical tools, stents, and fasteners and bone screws etc. Machining of this material by conventional approach is extremely difficult and results in deterioration in part quality, high cost, environmental footprints, and energy and resource consumption. It compels to explore and develop novel techniques to machine this material. Wire spark erosion machining also known as wire electric discharge machining (Wire-EDM) removes material by thermoelectric erosion where occurrence of spark between two electrodes i.e. workpiece (anode) and wire tool (cathode) melt and vaporize material and shape or geometry formation takes place [3]. Wire spark erosion machining which is an advanced process has been attempted to machine NiTi shape memory alloys and good results in terms of part quality and machinability enhancement are reported [4-7]. There is a scarcity of work on Wire-EDM of Ni rich NiTi, and still more detailed research is required to be done. The present work fulfils this gap.

The work reported in this paper is a part of the detailed investigation conducted on Wire-EDM of $Ni_{55.8}Ti$ shape memory alloy. In this paper mainly experimentation details, effect of Wire-EDM parameters on cutting rate (that directly affect productivity) and its optimization are reported.

2. Experimental details

In the present work, the experiments have been conducted on Electronica make Ecocut (Elplus 15) wire-cut electric discharge machine. The commercially used brass wire of 0.25mm diameter is used as an electrode. The deflections in the electrode were eliminated by the inbuilt system of wire-tension. In this process a gap is maintained in brass wire and work-piece with the help of in-built micro-processors. Deionized water has been used as a dielectric to flush away the debris. The chemical composition of work material Ni55.8Ti is given in Table 1. The initial diameter of the SMA was 25mm which was reduced up to a diameter of 16mm using low speed turning process. It was then machined in form of cylindrical pieces at different parameter set and the final dimension of the material was ϕ16mm with 2.5 mm heights. The 16 specimens have been cut as shown in Figure 1.

Since WEDM process is affected by number of control parameters, therefore a systematic planning is required to perform the experiments. In the present research work, four process parameters, namely, spark gap voltage (SV), pulse on-time (Ton), pulse off-time (Toff) and wire feed rate (WF) were selected at four levels. The design of experiments was done using Taguchi based L_{16} orthogonal array [8]. The levels of process parameters (variable and fixed) are depicted in Table 1. The cutting rate (CR) was directly recorded from the machine display. The CR at three places is recorded and the average of all three values is used in the present work.

Fig. 1. Experimental setup for WEDM of $Ni_{55.8}Ti$.

Table 1. Machining parameters and material composition

Variable parameters					
Machining Parameter	**Unit**	**Levels**			
		L1	**L2**	**L3**	**L4**
SV	V	20	30	40	50
T_{on}	μs	0.35	0.5	0.85	1
T_{off}	μs	9	11.5	15	24
WF	m/min	3	6	9	12
Fixed parameters					
Electrode material		Brass (ϕ0.25mm)			
Work material		NiTi SMA			
Dielectric fluid		Deionized water			
Dielectric pressure		High			
Conductivity of dielectric (mho)		±(20-24)			
Material composition		Ni- 55.8% Ti-43.9% C-0.3%			

3. Results and discussion

The experimental combinations and corresponding values of cutting rate (CR) are given in Table 2, whereas Fig. 2 depicts the variation of cutting rate with Wire-EDM parameters. It has been observed that with the increase of servo voltage the CR initially increases then at large value of SV, the CR found to be decreased. This is due the fact that with the increase of SV, the discharge energy in the spark gap increases which increases the CR. At higher value of SV, the CR decreases due to the waiting period of spark. The CR found to be increased with the Ton due to the enlargement of the current on-time in the circuit. This on-time increases the discharge energy in the circuit, which increases the erosion rate in the spark gap. Toff is the current off-time in the circuit, so a smaller value of off-time favors the higher CR due to large intensity of current within the circuit. The CR decreases with increase of Toff as shown in Fig. 2 due to decrement in the current value within a stipulated period of time. Wire feed (WF) has a positive effect on CR, so a large WF favors CR. The reason behind this is that with the increase of WF, a fresh or new portion of wire comes into action and helps to easily remove the material from the work piece within a specified period of time.

Table 2 Experimental design and results

Sr. No	**SV**	**T_{on}**	**T_{off}**	**WF**	**Cutting rate (mm/min)**
1	20	0.35	9	3	0.73
2	20	0.55	11.5	6	1.22
3	20	0.8	15	9	1.76

4	20	1	24	12	2.17
5	30	0.35	11.5	9	1.24
6	30	0.55	9	12	2.2
7	30	0.8	24	3	2.03
8	30	1	15	6	2.14
9	40	0.35	15	12	1.2
10	40	0.55	24	9	1.31
11	40	0.8	9	6	2.64
12	40	1	11.5	3	2.6
13	50	0.35	24	6	0.63
14	50	0.55	15	3	1.3
15	50	0.8	11.5	12	2.16
16	50	1	9	9	2.81

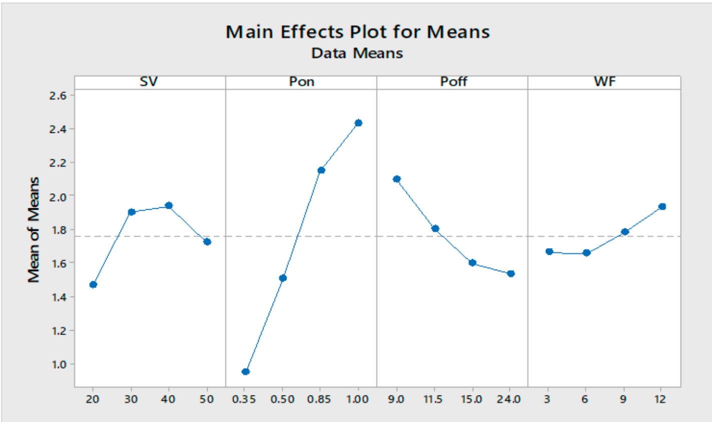

Fig. 2. Variation of cutting rate of $Ni_{55.8}Ti$ with WEDM parameters.

Taguchi Method solves the single response and does not provide the model for the multi-response problem. It does not provide a suggested optimal setting in between the two consecutive levels. So, to find out the accurate optimal setting the Taguchi OA further solved by Regression analysis which is an important tool for modeling of machining processes [9]. In this method, one empirical model was developed in which one response was affected by the four input parameters. The regression coefficients as evaluated are given in Equation 1.

$$CR = 0.261 + 0.00800 \times SV + 2.176 \times Pon - 0.0325 \times Poff + 0.0308 \times WF \quad (1)$$

Genetic algorithm (GA) is an evolutionary optimization technique in which a mathematical model is solved by developing a fitness function [10]. The fitness function investigates the chromosome values and a higher chromosome value from the offspring and parent will be forwarded for next generation. The process of investigation of chromosomes lasts till the satisfactory results are obtained as per the stopping criteria. The new chromosomes have no chance of further improvement as the stopping criterion is to be set in such a way that the obtained solution represents the best value as compared to children and parents.

Mathematical model was solved by fitness function according to the lower and upper limits of the parameters as given by the equation 2 to 5.

$$20 \leqslant SV \leqslant 50 \quad (2)$$

$$0.35 \leqslant Ton \leqslant 1 \quad (3)$$

$$9 \leqslant Toff \leqslant 24 \quad (4)$$

$$3 \leqslant WF \leqslant 12 \quad (5)$$

There are a number of ways by which the optimization of CR can be processed in GA. A number of combinations of operating parameters i.e. migration, cross-over and selection can be used to get predicted CR and process parameters settings. Every time with the change of operating parameter setting the new genes were formed and combined with the parent. So, different combinations of selection, crossover and migrations were solved for best CR. After alternations in the operating parameters, it was found that the maximum cutting rate was obtained at crossover ratio is 1.4 with single point type. Migration is of uniform type with a ratio of 0.5 and is in forward direction.

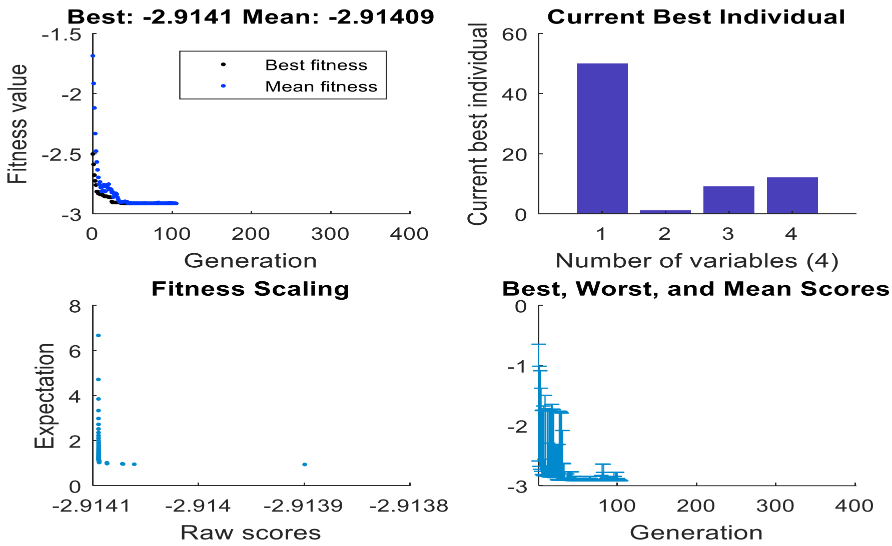

Fig. 3 Best fitness, best individual expectation and range plot in GA optimization.

Figure 3 depicts the best range, best fitness, best individual and expectation plot for CR. It is clear from Figure 4 that with the increase of the number iterations the mean fitness value decreases. The black dots coincide with the blue dot after 47 iterations and blue covers the black at 53 iterations. Best individual graph suggests the optimum combinations of the process parameters at which maximum CR can be obtained. Expectation plot reveals that the cluster of blue dots at 2.91, so the predicted value of CR as per the optimum combination of process parameters is 2.91. Finally, the range plot shows that with the increase of number of iterations, the range is found to be decreased. This fact suggests that with the increase in iterations in a given population better solution were obtained with the combination of parents and off-springs.

Three confirmations experiments have been performed at the suggested (by GA) optimal setting and a good agreement with the predicted value of CR is observed (see Table 3). It is claimed that the cutting rate of machining of Ni55.8Ti by WEDM process has been optimized by GA technique. At the optimized setting, surface roughness of the material was also evaluated. The surface roughness profile of the specimens, which were machined at optimized setting is shown in Figure 4. The measured value of average surface roughness is 2.712 µm.

Table 3 Results of optimization

Machining parameters	**CR (mm/min)**	
SV- 50 V	GA	Confirmation Expt
Ton- 1 µs		
Toff- 9 µs	2.91	2.96
WF- 12 m/min		

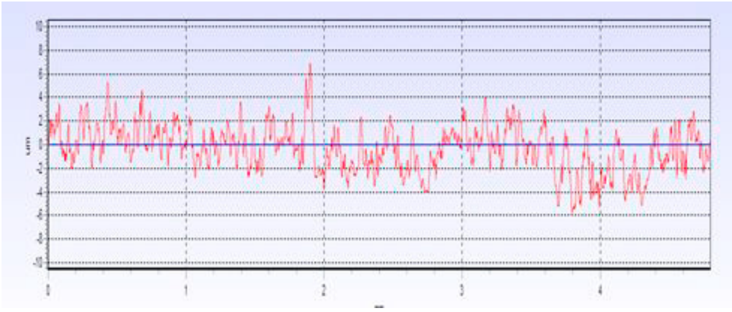

Fig. 4 Roughness profile of the machined surface at the GA based optimum setting of WEDM

4. Conclusion

The conclusions drawn from the present work are discussed below:

1. Low value of Toff, high value of SV, Ton and WF favours the cutting rate (CR). CR is significantly affected by Ton and Toff as compared to SV and WF.
2. Regression model for cutting rate has been developed to establish the relationship between WEDM parameters and cutting rate for future prediction purposes.
3. The range and mean fitness decreases with the increase in iterations during genetic programming.
4. GA based optimization of WEDM parameters has improved cutting rate and hence productivity for machining of $Ni_{55.8}Ti$ shape memory alloy.

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