



King Saud University
Journal of King Saud University – Engineering Sciences

www.ksu.edu.sa
 www.sciencedirect.com



ORIGINAL ARTICLES

Optimization of material removal rate during electrical discharge machining of cryo-treated NiTi alloys using Taguchi's method

Vaibhav Gaikwad^a, VijayKumar S. Jatti^{b,*}

^a Department of Production Engineering, K. K. Wagh Institute of Engineering Education and Research, Nashik 422003, Maharashtra State, India

^b Mechanical Engineering Department, Symbiosis Institute of Technology (SIT), Symbiosis International University (SIU), Lavale, Pune 412 115, Maharashtra State, India

Received 21 January 2016; accepted 24 April 2016

KEYWORDS

NiTi alloy;
 Taguchi's method;
 ANOVA;
 Material removal rate

Abstract To withstand in global manufacturing market it is necessary to acquire new technology for producing new products. To achieve this advanced material plays an important role. NiTi alloy is one such class of advanced material which has unique properties such as biocompatibility, high strength, high corrosion resistance, shape memory effect etc. Due to such property these alloys have wide application in the field of defence, aerospace, and medicine. As these applications required high accuracy, precision and high strength of NiTi these are difficult to machine by conventional machining processes. Hence to machine this advanced material non-conventional machining processes i.e. electric discharge machining is employed. However EDM has a wide range of process parameter and the aim of EDM users and manufacturers is to achieve optimal performance of EDM. In view of this objective the present study focuses on optimization of electric discharge machining process parameter for maximization of material removal rate while machining of NiTi alloy. In the present study gap current, pulse on time, pulse off time, workpiece electrical conductivity, and tool conductivity were considered as process variables. Experiments were carried out as per Taguchi's L_{36} orthogonal array. Based on the analysis it was found that work electrical conductivity, gap current and pulse on time are the significant parameters that affect the material removal rate. The optimized material removal rate obtained was $7.0806 \text{ mm}^3/\text{min}$ based on optimal setting of input parameter.

© 2016 The Authors. Production and Hosting by Elsevier B.V. on behalf of King Saud University. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

* Corresponding author.

E-mail addresses: vsgaikwad113@gmail.com (V. Gaikwad), vijaykumar.jatti@sitpune.edu.in (VijayKumar S. Jatti).

Peer review under responsibility of King Saud University.



Production and hosting by Elsevier

<http://dx.doi.org/10.1016/j.jksues.2016.04.003>

1018-3639 © 2016 The Authors. Production and Hosting by Elsevier B.V. on behalf of King Saud University.

This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Please cite this article in press as: Gaikwad, V., Jatti, V.S. Optimization of material removal rate during electrical discharge machining of cryo-treated NiTi alloys using Taguchi's method. Journal of King Saud University – Engineering Sciences (2016), <http://dx.doi.org/10.1016/j.jksues.2016.04.003>

1. Introduction

To withstand in today's global manufacturing market it is necessary to adopt a new technology. The demand of this new technology is to acquire smart material such as NiTi alloy. NiTi is a class of smart material which possesses unique properties such as super elasticity, high strength, biocompatibility etc. NiTi alloy is widely used in the field of defence, aerospace, and medicine. As this alloy has unique property and application machining of this alloy is difficult using conventional machining processes therefore machining of this alloy is carried out using non-conventional machining processes such as electric discharge machining (EDM). EDM is the processes in which electrical energy is transferred into the thermal energy and erosive action leads to removal of material using flushing fluid.

Chen et al. (2007) studied the electro discharge machining of TiNiCr and TiNiZr ternary SMA. In this research conventional tungsten arc welding technique was implemented for the preparation of TiNiCr and TiNiZr ternary SMA. They concluded that MRR exhibits an inverse relationship to the product of the alloys melting temperature and thermal conductivity. Material removal rate will increase with both the increase in current as well as pulse on. From this research study they found that TiNiCr has a larger Ra value than TiNiZr and the thickness of recast layer varies with pulse on time and has a minimum value at maximum MRR. Chen et al. (2007) investigated the electro discharge machining of NiAlFe ternary SMA. The conventional tungsten arc welding technique is being practised to get ready NiAlFe. In this research it is concluded that MRR for NiAlFe is more as compared to TiNiZr and thickness of recast layer increases at the early stage and declines to a minimum value at the maximal MRR. Also the surface roughness (Ra) value of $\text{Ni}_{60}\text{Al}_{24.5}\text{Fe}_{15.5}$ is large as that of TiNiZr. Prihandana et al. (2011) investigated the effect of vibration on electric discharge machine. Material used for conducting these experiments is stainless steel (SS-304) with a low frequency vibration. This research study shows that use of a low frequency vibration improves the material removal rate and diminishes tool wear rate and surface finish. Singh et al. (2012) studied the effect of continuous and discontinuous vibration on work piece. In this study experiments were carried out using Taguchi's L_{18} orthogonal array. For experimentation high chromium high carbon steel is being used as work piece and copper is being used as tool material. On the basis of experiment they concluded that discontinuous vibrations give more MRR and TWR. Also the intensity of development of cracks is more in case of discontinuous vibration as compared with continuous vibration. Sabouni and Daneshmand (2012) conducted a research on EDM process parameter for NiTi SMA using graphite tool. For experimentation L_{18} Taguchi's DOE is being used. To improve the accuracy of experiments and to prevent the effect of oil-based dielectrics in reacting with the workpiece surface de-ionized oil water with an EC of less than 1 ms (micro Siemens) has been implemented along with the constant spray type of flushing. In this research study voltage is kept at 2 levels and pulse on, pulse off, gap current is at 3 levels. Daneshmand et al. (2013) conducted a research study on NiTi shape memory alloy using copper as a tool and de-ionized water as a flushing fluid. Experiments were carried out using

Taguchi's L_{18} orthogonal array. From this study they concluded that material removal rate and tools wear rate increase with an increase in current and pulse on time, also tool wear rate with de-ionized water is less as compared to kerosene. Daneshmand et al. (2013) conducted a research on performance measure of output parameters of EDM using rotational tool, tool will be rotating at 200 rpm. Taguchi's DOE method is being implemented with L_{18} orthogonal array. Researchers investigated that MRR in rotational EDM is less as compared to traditional EDM by effect of current, pulse on, pulse off and voltage. Rotational tool decreases the breakdown resistance of dielectric hence MRR in rotational toll is less. Tool wear rate in case of rotational EDM decreases compared to traditional EDM with regards to gap current, pulse on time, pulse off time and gap voltage. This happens because there is decrease in the dielectric breakdown resistance by tool electrode rotation gap between tool and workpiece will increase and plasma channel becomes wide as a result of this electro discharge thermal energy distributes in large area so that electrical power density and MRR declines as a result TWR reduce consequently. Malek et al. (2011) investigated the electric discharge machining of B_4C - TiB_2 composites with respectively 30, 40 and 60 vol.% TiB_2 . They found that 40 vol.% TiB_2 give optimal material removal rate and with an increase in concentration of TiB_2 surface roughness increases. They also found that an increase in the TiB_2 leads to an increase in thermal conductivity. Pradhan and Biswas (2009) investigated the effect of EDM processes parameter on AISI D2 tool steel with copper electrode. For experimentation they implemented response surface methodology. They concluded from this research that surface roughness has a direct relationship with the current and pulse on time. Sohani et al. (2009) investigated the effect of various shapes of electrode such as triangular, square, and circular on EDM processes parameter. They used response surface methodology for conduction of experiments. From this research study they concluded that the best tool shape for higher MRR and lower TWR is circular. They also concluded that MRR increases linearly and TWR non-linearly with the spark energy. Sohani et al. (2009) investigated the effect of various shapes of electrode such as triangular, square, and circular on EDM processes parameter. They used response surface methodology for conduction of experiments. From this research study they concluded that the best tool shape for higher MRR and lower TWR is circular. They also concluded that MRR increases linearly and TWR non-linearly with the spark energy. Lin et al. (2009) studied the magnetic force assist electrical discharge machine using Taguchi's L_{18} orthogonal array. From this research they concluded that MRR is improved and TWR is decreased as that of the conventional machining with magnetic assist EDM. They found that MRR is increased three times as that of conventional EDM. Manjaiah et al. (2015) investigated wire electric discharge machining of $\text{Ti}_{50}\text{Ni}_{50-x}\text{Cu}_x$ shape memory alloy. Performance measures considered during the machining were surface roughness, material removal rate, surface topography and metallographic changes. It was noted during the experimentation that with brass and zinc coated wire servo voltage, pulse off time and pulse on time were significant parameters which affect the MRR and surface roughness. Manjaiah et al. (2014) investigated machining of NiTi alloy on wire electric discharge machine. In this research experiments were conducted as per L_{27} orthogonal array. During this research anal-

ysis of variance and analysis of means were performed to optimize the processes. From this research it was concluded MRR is affected significantly by pulse on time. From review of literature it was observed that researchers have used design of experiments and Taguchi's method during machining of different workpiece materials. But very few researchers have tried to establish the relationship between input parameter (gap current, gap voltage, pulse on time and pulse off time) and EDM performance measures during machining of NiTi alloy. Even the effect of workpiece and tool electrode electrical conductivity was not considered during machining of NiTi alloy. In EDM process the workpiece and tool electrical and thermal conductivity plays an important role to enhance the efficiency of the EDM process. Thus in this study workpiece and tool electrode electrical conductivity was considered as an input parameter. The aim of the present study was to optimize electric discharge machining process parameter for maximization of material removal rate during of machining of NiTi alloy. In the present study gap current, pulse on time, pulse off time, workpiece electrical conductivity, and tool conductivity were considered as process variables. Experiments were carried out as per Taguchi's design of experiments L_{36} orthogonal array.

2. Materials and methodology

In present study NiTi alloy was selected as workpiece material and electrolytic copper was used as tool electrode. NiTi samples were cut into size of $\phi 20 \text{ mm} \times 20 \text{ mm}$ length. Tool electrode of size $83 \text{ mm} \times 90 \text{ mm}$ length was used during the experimentation. Both the workpiece and tool are cryo-treated at -185°C at cryospace, Pune. Electrical conductivity of workpiece and tool was obtained from electrical resistivity testing system. From literature review it was observed that researchers have tried to establish the relationship between input parameter and responses during machining of NiTi alloy. However, the effect of workpiece and tool electrode electrical conductivity was not considered during machining of NiTi alloy. In EDM process the workpiece and tool electrical and thermal conductivity plays an important role to enhance the efficiency of the EDM process. Thus in this study workpiece and tool electrode electrical conductivity was considered as an input parameter. Workpiece and tool electrode are considered at two levels and gap current, pulse on time and pulse off time were considered at three levels. The number of input parameters along with their levels was decided based on the pilot study and literature review. To select the Taguchi's orthogonal array the degrees of freedom of each input parameter and levels are considered. For the present study the workpiece and tool are considered at two levels, thus each contributes one degree of freedom. Gap current, pulse on time and pulse off time were considered at three levels, hence each contributes two degrees of freedom. Thus a total of eight degrees of freedom was obtained and mixed levels of input parameters were considered for the present study. Taguchi's L_{36} ($2^2 \times 3^3$) mixed orthogonal array satisfies both the conditions of i.e., degrees of freedom (35) and mixed levels of input parameters. Thus, in this study experiments were carried out as per Taguchi's L_{36} ($2^2 \times 3^3$) mixed orthogonal array. Experiments were carried out on die sink type of electric discharge machine of Electronic machine tool limited make. Digital

weighing balance of model GR 300 with accuracy 0.0001 was used to measure the weight of workpiece before and after machining. Flushing pressure and gap voltage were kept constant at 0.5 kg/cm^2 and 55 V respectively, throughout the experiments. Material removal rate was calculated using Eq. (1) for all the experimental conditions.

$$\text{MRR} = \frac{(W_1 - W_2) \times 1000}{\rho \times t} \quad (1)$$

where W_1 and W_2 are the weight of workpiece before and after machining respectively (grams), ρ is the density of workpiece in (gm/cc), t is the machining time in minutes.

Fig. 1 shows the machine tool used for experimentation and Fig. 2 shows the EDM operation. Figs. 3 and 4 show the workpiece and tool electrode respectively. Table 1 shows various EDM process parameters and their levels.

3. Results and discussion

In order to study the effect of EDM process parameter on material removal rate, experiments were designed using Taguchi's L_{36} orthogonal array as shown in Table 2. The average values of material removal rate for each parameter at levels 1, 2 and 3 for S/N data are plotted in Fig. 5 and raw data are plotted in Fig. 6. In the present study analysis of variance was performed at 5% level of significance. It was found that



Figure 1 Machine tool.

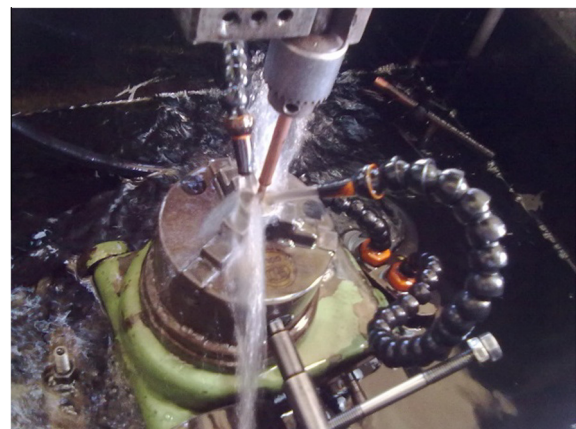


Figure 2 EDM operation.

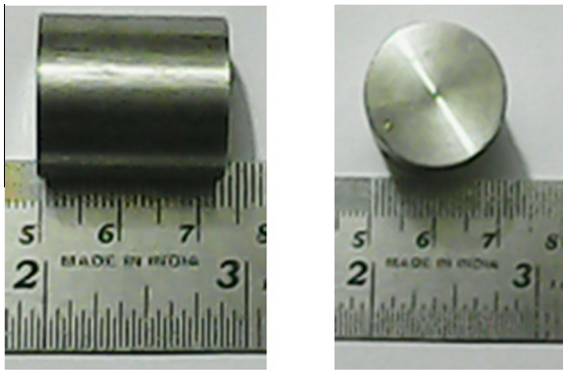


Figure 3 NiTi workpiece.



Figure 4 Copper electrode.

Table 1 EDM process parameters with their levels.

Factors	Levels		
	1	2	3
Workpiece electrical conductivity [S/m]	3267 [untreated]	4219 [treated]	–
Tool electrical conductivity [S/m]	10000 [untreated]	26316 [treated]	–
Gap current [A]	8	12	16
Pulse on time [μs]	13	26	38
Pulse off time [μs]	5	7	9

Table 2 Taguchi's experimental design with observed values.

Workpiece electrical conductivity [S/m]	Tool electrical conductivity [S/m]	Gap current [A]	Pulse on time [μs]	Pulse off time [μs]	MRR [mm ³ /min]
3267	10,000	8	13	5	1.09
3267	10,000	12	38	7	4.56
3267	10,000	16	63	9	5.56
3267	10,000	8	13	5	1.08
3267	10,000	12	38	7	4.57
3267	10,000	16	63	9	5.57
3267	10,000	8	13	7	1.06
3267	10,000	12	38	9	4.51
3267	10,000	16	63	5	5.63
3267	26,316	8	13	9	1.32
3267	26,316	12	38	5	4.29
3267	26,316	16	63	7	4.91
3267	26,316	8	38	9	1.97
3267	26,316	12	63	5	3.62
3267	26,316	16	13	7	5.07
3267	26,316	8	38	9	1.96
3267	26,316	12	63	5	3.68
3267	26,316	16	13	7	5.02
4219	10,000	8	38	5	3.91
4219	10,000	12	63	7	4.23
4219	10,000	16	13	9	6.4
4219	10,000	8	38	7	3.68
4219	10,000	12	63	9	4.14
4219	10,000	16	13	5	6.82
4219	10,000	8	63	7	2.85
4219	10,000	12	13	9	5.42
4219	10,000	16	38	5	7.08
4219	26,316	8	63	7	2.41
4219	26,316	12	13	9	5.76
4219	26,316	16	38	5	6.36
4219	26,316	8	63	9	2.29
4219	26,316	12	13	5	5.84
4219	26,316	16	38	7	6.34
4219	26,316	8	63	5	2.98
4219	26,316	12	13	7	5.78
4219	26,316	16	38	9	6.31

gap current and pulse on time are significant parameters that affect the material removal rate. Then after eliminating the insignificant parameter pooled ANOVA was performed. Tables 3 and 4 show the pooled ANOVA table for S/N data and raw data respectively. Tables 5 and 6 show the Taguchi's response table for S/N data and raw data respectively. All the analyses were carried out using MINITAB 16 statistical software. From Figs. 5 and 6 it can be seen that to get maximized value of material removal rate, the optimal setting of workpiece electrical conductivity is 4219 S/m, gap current is 12 A and pulse on time is 38 μs.

On the basis of optimal setting of process parameters confirmatory experiments were performed to validate obtained results. Eq. (2) was used to predict the mean value of MRR based on optimal setting of input parameter.

$$\mu_{MRR} = \overline{A_2} + \overline{C_3} + \overline{D_2} - 2\overline{T} \quad (2)$$

\overline{T} = overall mean of MRR = 4.28 mm³/min

$\overline{A_2}$ = average value of MRR at second level of workpiece electrical conductivity = 4.922 mm³/min

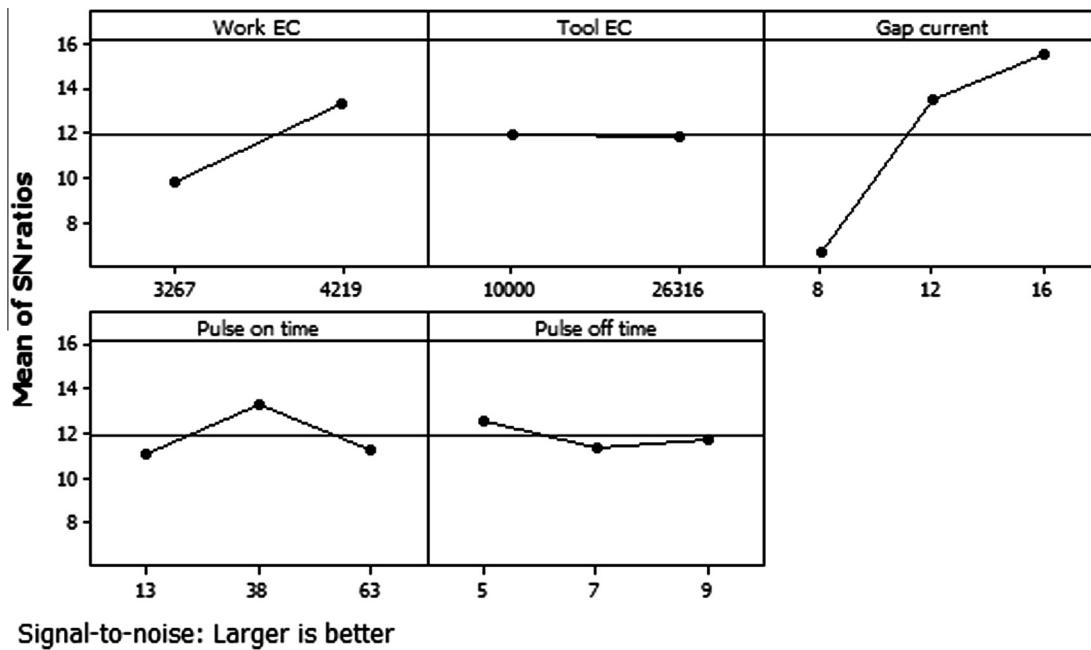


Figure 5 Effect of input parameter on MRR (S/N data).

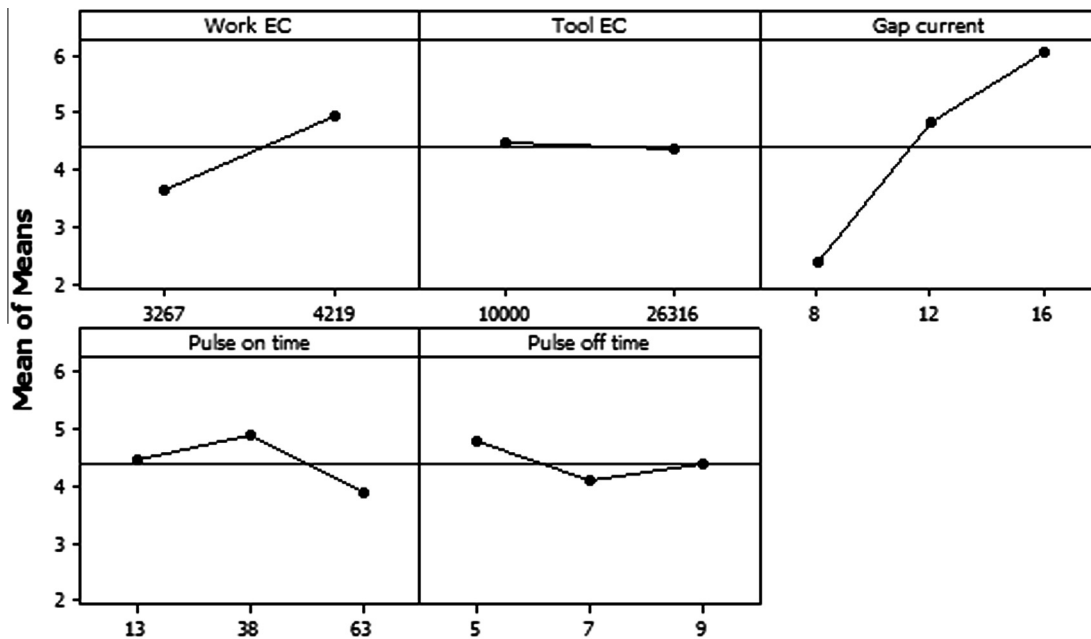


Figure 6 Effect of input parameter on MRR (raw data).

Table 3 Pooled ANOVA table for MRR (S/N data).

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Work EC	1	89.85	89.85	89.848	28.98	0.000
Gap current	2	441.95	432.88	216.442	69.81	0.000
Pulse on time	2	20.38	20.38	10.192	3.29	0.055
Residual error	24	74.41	74.41	3.100		
Total	29	626.59				

Table 4 Pooled ANOVA table for MRR (raw data).

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Work EC	1	11.955	11.955	11.9546	50.46	0.000
Gap current	2	70.683	67.542	33.7708	142.53	0.000
Pulse on time	2	2.226	2.226	1.1129	4.70	0.019
Residual error	24	5.686	5.686	0.2369		
Total	29	90.550				

Table 5 Response table for MRR (S/N ratio data, Lager-the-better).

Level	Work EC	Gap current	Pulse on time
1	9.790	6.609	11.095
2	13.323	13.548	13.304
3		15.572	11.330
Delta	3.533	8.963	2.210
Rank	2	1	3

Table 6 Response table for material removal rate (raw data).

Level	Work EC	Gap current	Pulse on time
1	3.633	2.355	4.453
2	4.922	4.818	4.900
3		6.047	3.867
Delta	1.289	3.692	1.033
Rank	2	1	3

\bar{C}_3 = average value of MRR at third level of gap current = 6.047 mm³/min

\bar{D}_2 = average value of MRR at second level of pulse on time = 4.9 mm³/min

$\mu_{MRR} = 7.309$ mm³/min

The 95% confidence intervals of confirmation experiments (CI_{CE}) and population (CI_{pop}) are calculated using formulae;

$$CI_{CE} = \sqrt{F_z(1, f_e) V_e \left(\frac{1}{n_{eff}} + \frac{1}{R} \right)} \quad (3)$$

$$CI_{pop} = \sqrt{\frac{F_z(1, f_e) V_e}{n_{eff}}} \quad (4)$$

where

$F_z(1, f_e)$ = the F ratio at the confidence level of $(1 - \alpha)$ against DOF 1 and error degree of freedom f_e .

$$n_{eff} = \frac{N}{1 + [\text{DOF associated in the estimate of mean response}]}$$

$$n_{eff} = 36/(1 + 5) = 6$$

N = total number of results = 36

R = sample size for confirmation experiments = 3

V_e = error variance = 0.2369

f_e = error DOF = 24

$$F_z(1, f_e) = 4.26$$

$$CI_{CE} = \pm 0.7103$$

$$CI_{pop} = \pm 0.4101$$

The predicted confidence interval for confirmation experiments is:

$$\text{Mean } \mu_{MRR} - CI_{CE} < \mu_{MRR} < \text{Mean } \mu_{MRR} + CI_{CE}$$

$$6.5987 < \mu_{MRR} < 8.0193$$

The 95% confidence interval of the population is:

$$\text{Mean } \mu_{MRR} - CI_{pop} < \mu_{MRR} < \text{Mean } \mu_{MRR} + CI_{pop}$$

$$6.8989 < \mu_{MRR} < 7.7191$$

The optimal values of process variables at their selected levels are as follows:

Second level of work EC (A_2): 4219 S/m

Third level of gap current (C_3): 16 A

Second level of pulse on time (D_2): 38 μ s

Table 7 shows the result of confirmation experiments. From these experiments it was observed that actual value of MRR lies within the confidence intervals at 95% confidence level.

4. Conclusion

This paper discusses the optimization of material removal rate during machining of NiTi alloy in die sink electrical discharge machine. Gap current, pulse on time, pulse off time, workpiece electrical conductivity, and tool conductivity were considered as input process variables. Based on the analysis it was found that work electrical conductivity, gap current and pulse on time are the significant parameters that affect the material removal rate. Based on Taguchi's analysis the optimal settings of input parameter are second level of work EC (A_2): 4219 S/m, third level of gap current (C_3): 16 A and second level of pulse on time (D_2): 38 μ s for achieving maximum value of material removal rate. The optimized material removal rate obtained was 7.0806 mm³/min based on optimal setting of input parameter and the obtained material removal rate lies between the calculated confidence interval. Hence, Taguchi's method is useful in optimizing single objective of electrical discharge machining process parameters. In future the work can be extended to discuss the tool wear rate and surface roughness during machining of NiTi alloy which was not considered in the present study. Further, a multi-objective optimization of responses such material removal rate, tool wear rate and surface roughness can be carried out using non-traditional optimization methods.

Table 7 Confirmation experiment result.

Responses	Optimal set of process variables	Predicted optimal value of response	Predicted confidence intervals at 95% confidence level	Actual value (average of three confirmation experiments)
MRR	$A_2C_3D_2$	7.309 mm ³ /min	$CI_{CE}: 6.5987 < \mu_{MRR} < 8.0193$ $CI_{pop}: 6.8989 < \mu_{MRR} < 7.7191$	7.0806 mm ³ /min

References

- Chen, S.L., Hsieh, S.F., Lin, H.C., Huang, J.S., 2007. EDM of TiNiCr and TiNiZr ternary SMA. *Mater. Sci. Eng.* 445–446, 486–492.
- Chen, S.L., Hsieh, S.F., Lin, H.C., Huang, J.S., 2007. EDM of NiAlFe ternary SMA. *J. Alloys Compos.* 464, 446–451.
- Daneshmand, S., Kahrizi, E.F., Neyestanak, A.A., Ghahi, M.M., 2013. Experimental investigation into EDM of NiTi SMA using Rotational Tool. *Int. J. Electrochem. Sci.* 8, 7484–7497.
- Daneshmand, S., Kahrizi, E.F., Abedi, E., Abdolhosseini, M.M., 2013. Influence of machining parameter on electro discharge machining of NiTi SMA. *Int. J. Electrochem. Sci.* 8, 3095–3104.
- Lin, Y.C., Chen, Y.F., Wang, D.A., Lee, H.O., 2009. Optimization of machining parameters in magnetic force assisted EDM based on Taguchi method. *J. Mater. Processes Technol.* 209, 3374–3383.
- Malek, O., Vleugels, J., Vanmeensel, K., Huang, S., Liu, S.V., Berghe, A., Datye, K., Hsi Wu, K., Lauwers, B., 2011. Electrical discharge machining of B₄C–TiB₂ composites. *J. Eur. Ceram. Soc.* 31, 2023–2030.
- Manjaiah, M., Narendranath, S., Basavarajappa, S., Gaitonde, V.N., 2014. Wire electric discharge machining characteristics of titanium nickel shape memory alloy. *Trans. Nonferrous Met. Soc. China* 24, 3201–3209.
- Manjaiah, M., Narendranath, S., Basavarajappa, S., Gaitonde, V.N., 2015. Effect of electrode material in wire electro discharge machining characteristics of Ti₅₀Ni_{50-x}Cu_x shape memory alloy. *Precis. Eng.* 41, 68–77.
- Pradhan, M.K., Biswas, C.K., 2009. Modelling and analysis of process parameters on surface roughness in EDM of AISI D2 tool steel by RSM approach. *Int. J. Eng. Appl. Sci.* 5 (5), 346–351.
- Prihandana, G.S., Mahardika, M., Hamdi, M., Mitsui, K., 2011. Effect of low-frequency vibration on workpiece in EDM processes. *J. Mech. Sci. Technol.* 25, 1231–1234.
- Sabouni, H.R., Daneshmand, S., 2012. Investigation of the parameter of EDM process performed on smart NiTi alloy using graphite tool. *Life Sci. J.* 9 (4), 504–510.
- Singh, J., Walia, R.S., Satsangi, P.S., Singh, V.P., 2012. Hybrid electric discharge machining process with continuous and discontinuous ultrasonic vibrations on workpiece. *Int. J. Mech. Syst. Eng.* 2, 22–33.
- Sohani, M.S., Gaitonde, V.N., Siddeswarappa, B., 2009. Investigations into the effect of tool shapes with size factor consideration in sink electrical discharge machining (EDM) process. *Int. J. Adv. Manuf. Technol.* 45, 1131–1145.