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Original article

Experimental investigation & optimisation of wire electrical discharge machining process parameters for $Ni_{49}Ti_{51}$ shape memory alloy

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ABSTRACT

Shape Memory Alloys (SMAs) are unique class of modern material with various functional properties such as pseudo-elasticity, biocompatibility, high specific strength, high corrosion resistance and high anti-fatigue property. The machining of these SMAs is difficult by conventional machining processes due to strain-hardening effect which changes the properties of materials and it is found that non-conventional machining processes are more suitable to machine them. In present investigations, the experiments were performed on wire electrical discharge machining (WEDM) to study the interaction effects of the process parameter on surface characteristics of $Ni_{49}Ti_{51}$ SMA's by brass tool electrode. Peak current, pulse on time, pulse off time, wire tension and wire feed rate were taken as input parameters and their effect were analysed on material removal rate. Artificial neural network was adopted to develop and to train the experimental data using back-propagation neural network (BPNN) approach. The response surface methodology (RSM) was adopted to develop the second order mathematical based quadratic models. The recast layer formation and surface of machined materials were also analysed by the SEM characterization. It was noticed that the machined surface contains the surface cracks and uneven distribution of crater on the surface.

1. Introduction

Since the discovery of NiTi alloys, it has found applications in various fields due to their exclusive properties like resistance of fatigue, heat and force of impact. Nowadays NiTi has large applications in aerospace industry, orthodontics, micro-electrical systems (MEMS) etc. The machining of shape memory alloy is difficult by conventional machining process. To overcome the difficulties, Wire EDM non-conventional machining process have high protentional for the machining of SMAs. Wire EDM process is an electro thermal machining process and it uses a moving conductive wire and utilizes the energy of spark to melting and vaporize the specimen. Wire EDM can machine complex profile on a difficult-to-machine material. Sharma et al. (2017) and Manjaiah et al. (2016) reported that NiTi can be easily machined in a single-cutting operation, using wire EDM process, but after the first cut, un-machined surface area are major surface defects that reduce the shape memory effect. The effect of machining parameters was analysed on MRR and surface roughness.

Goyal et al. (2017) proposed that cryogenically treated tool electrode showed the major factor that influence the material removal rate and the surface roughness of the machined parts. Kumar and Ravichandran (2018) have fabricated AA7178-10 wt% ZrB2 MMC by stir casting process and after that WEDM machining was performed. The scanning electron microscope and energy dispersive X-Ray spectroscopy were used to analysis the surface characteristics. They found that peak current and pulse on time was important factors which affect the machining of Al7178-10 wt% ZrB2 MMC. Soni et al. (2017) showed that formation of surface defects such as micro cracks and micro voids occur at higher pulse on time. They claim that the at the high discharge energy the machining surface get damaged with provides the uneven distribution of craters on the surface. Rasheed et al. (2012) noticed that, capacitance as the most determine factor on MRR, TWR and Ra. They claim that surface roughness and tool wear rate were better at the low value of energy. The dimensional accuracy of the

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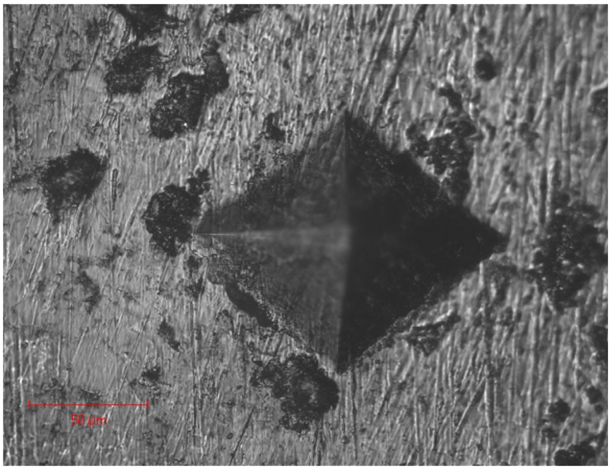

Fig. 1. Hardness measurement of $Ni_{49}Ti_{51}$ SMA.

machined holes was observed by the SEM analysis. Hsieh et al. (2016) analysed that, adding of Mo to NiTi, reduced the EWR, surface roughness and recast layer thickness because of increased melting temperature and thermal conductivity. The abilities of ANNs in taking the mathematical modelling between input parameters and output parameters for machining process. ANN tool box of MATLAB is utilized to develop the BPNN model. There are number of input process parameters in wire EDM that affects the performance of the result. In present study five input parameters are considered as training vector to develop the model between the input and output parameters. (Padhi et al. 2014; Singh and Misra, 2019). Tofigh et al. (2013) conducted experiment to identify the reinforcement of nano particles into aluminium alloy. The obtained results were verifying with the modelling of feed forward neural network methodology for the hardness, tensile and compressive yield stress properties. It was found that the predictions were reliable with the experimental values. Fard et al. (2013) performed experiments to consider the sustainable environment during the machining by wire EDM process of Al-SiC MMC. The L27 Taguchi's OA was developed to perform the trials and analysis the result of machining parameters on cutting velocity and surface roughness.

Kumar et al. (2016) reported WEDM as an appropriate technique to machine high strength temperature resistant materials with very little dimensional deviation. It was found that, deviation can be controlled by the optimum machining parameter setting. Liu et al. (2016) analysed that the white layer formed during WEDM of NiTi is of crystalline structure and not of amorphous nature, this was attributed towards the small amount of NiTi elements. Goyal (2017) experimental results shows that the obtained data can be useful for the EDM industry to obtain the better response from the machine. It was also proposed that investigation can be performed on the other advance materials by using a cryogenically treated tool electrode to analysis the performance characteristics of the machine.

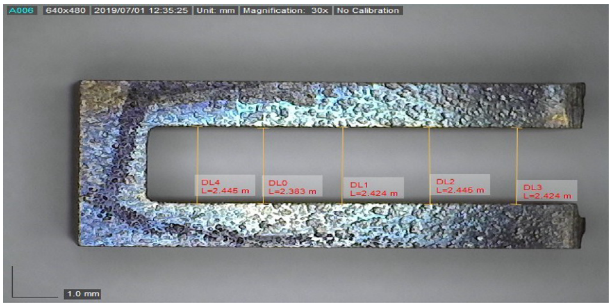

Fig. 2. Measurement of fabricated slots by WEDM Process.

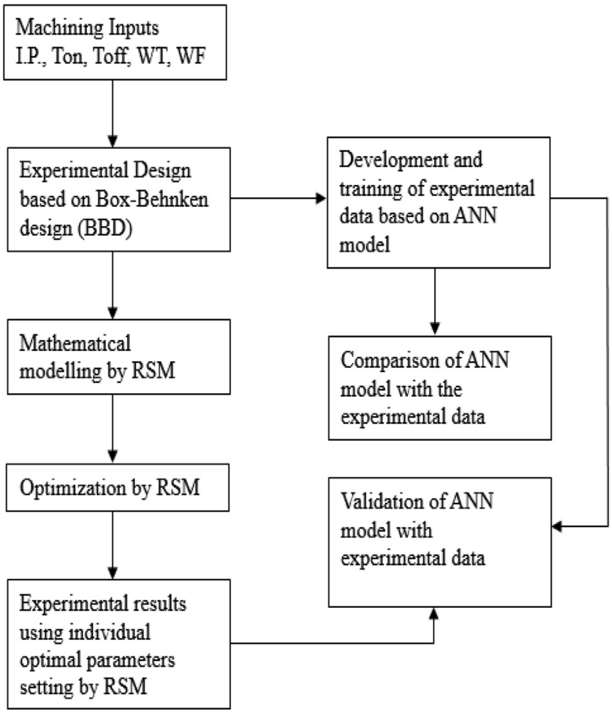

Fig. 3. Methodology for the Wire EDM process.

Garg et al. (2017) and Daneshmand et al. (2017) studied that ton and Toff depreciate the integrity of machined workpiece, which produces the surface defects on the machined surface. The optimum machining condition were also identified. Kuppuswamy and Yui (2017) fabricated micro slots, and profiles of size 0.5 mm in the shape memory alloys. The effort was made by the author to determine the optimal conditions to reduce the surface defects. The experiments were performed for the phase transition from austenitic to martensite and material undergoes elastic deformation when the temperature is increasers. The surface defects such as burr size have can be controlled by the feed and depth of cut during the micromachining the NiTi alloy. Kavimani et al. (2019)

Table 1
Process parameters and their range.

Symbol	Control Factor	Unit	Level 1	Level 2	Level 3
A	Current	Amp	4	6	8
B	Pulse on time	µs	60	90	120
C	Pulse off time	µs	15	30	45
D	Wire tension	cm^2/gm	11	13	15
E	Wire feed rate	m/min	4	6	8

Fig. 4. Tasks performed for present experiment work (a) Raw material, (b) WEDM set up (c) specimen after machining (d) Vickers hardness testing machine (e) measurement of slot by microscope (f) SEM machine.

investigated the WEDM characteristics for the machining of magnesium based MMC by Taguchi's and grey relation approach. The optimum machining condition for magnesium composite sample were one reinforced with 10 wt% SiC doped 0.2 wt% of r-GO under a minimum Ton (20 µs) value and maximum Toff (23 µs) and wf (2 m/min) level. It was suggested by the authors that the fabricated composite can be useful for the automobile and other relevant industries.

Kumar et al. (2013) and Gore and Patil (2018) reviewed the machining of alloys by the wire EDM process. The modelling of parameters and surface characterises were also discussed by the authors. Gopal (2019) conducted experiment on new material Mg/BN/CRT Hybrid metal matrix composite by using the multi objective optimization technique during the Wire EDM process. The reinforcement weight percentage and size were also

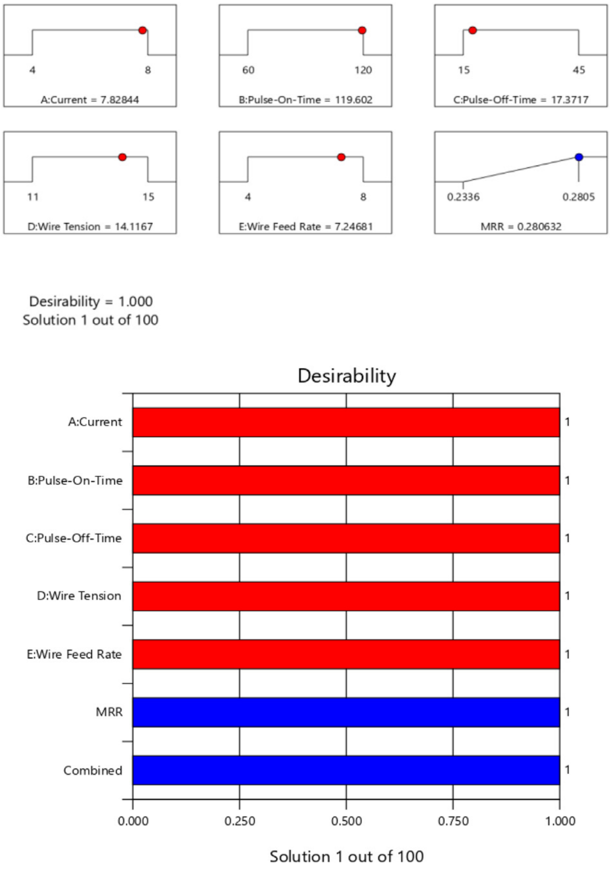

Fig. 5. Desirability index of MRR at optimized condition.

Table 2
Value of process parameters and MRR.

Run	Current	Pulse on time	Pulse off time	Wire tension	Wire feed rate	MRR	MRR Predicted	MRR Predicted (RSM)
	Amp	µs	µs	cm^2/gm	m/min	mm^3/min	mm^3/min	mm^3/min
1	4	60	15	11	4	0.2345	0.28044	0.234
2	4	60	15	11	6	0.2336	0.28046	0.2378
3	4	60	15	11	8	0.2456	0.28045	0.2415
4	4	90	30	13	4	0.2405	0.24261	0.2374
5	4	90	30	13	6	0.2398	0.25119	0.2408
6	4	90	30	13	8	0.2386	0.26233	0.2442
7	4	120	45	15	4	0.2336	0.23652	0.2378
8	4	120	45	15	6	0.2438	0.23635	0.2409
9	4	120	45	15	8	0.2456	0.2397	0.2439
10	6	60	30	15	4	0.2435	0.23711	0.2395
11	6	60	30	15	6	0.2425	0.23928	0.2411
12	6	60	30	15	8	0.2391	0.2452	0.2427
13	6	90	45	11	4	0.2369	0.24711	0.239
14	6	90	45	11	6	0.2416	0.24404	0.2414
15	6	90	45	11	8	0.2474	0.24627	0.2437
16	6	120	15	13	4	0.2666	0.26392	0.2644
17	6	120	15	13	6	0.2637	0.27088	0.2664
18	6	120	15	13	8	0.2706	0.2788	0.2684
19	8	60	45	13	4	0.2425	0.23644	0.2424
20	8	60	45	13	6	0.2347	0.23695	0.2429
21	8	60	45	13	8	0.2507	0.23983	0.2435
22	8	90	15	15	4	0.2557	0.24246	0.2555
23	8	90	15	15	6	0.2518	0.24664	0.2557
24	8	90	15	15	8	0.2586	0.26228	0.2559
25	8	120	30	11	4	0.2754	0.2783	0.2742
26	8	120	30	11	6	0.2805	0.276	0.2751
27	8	120	30	11	8	0.2686	0.27546	0.2761

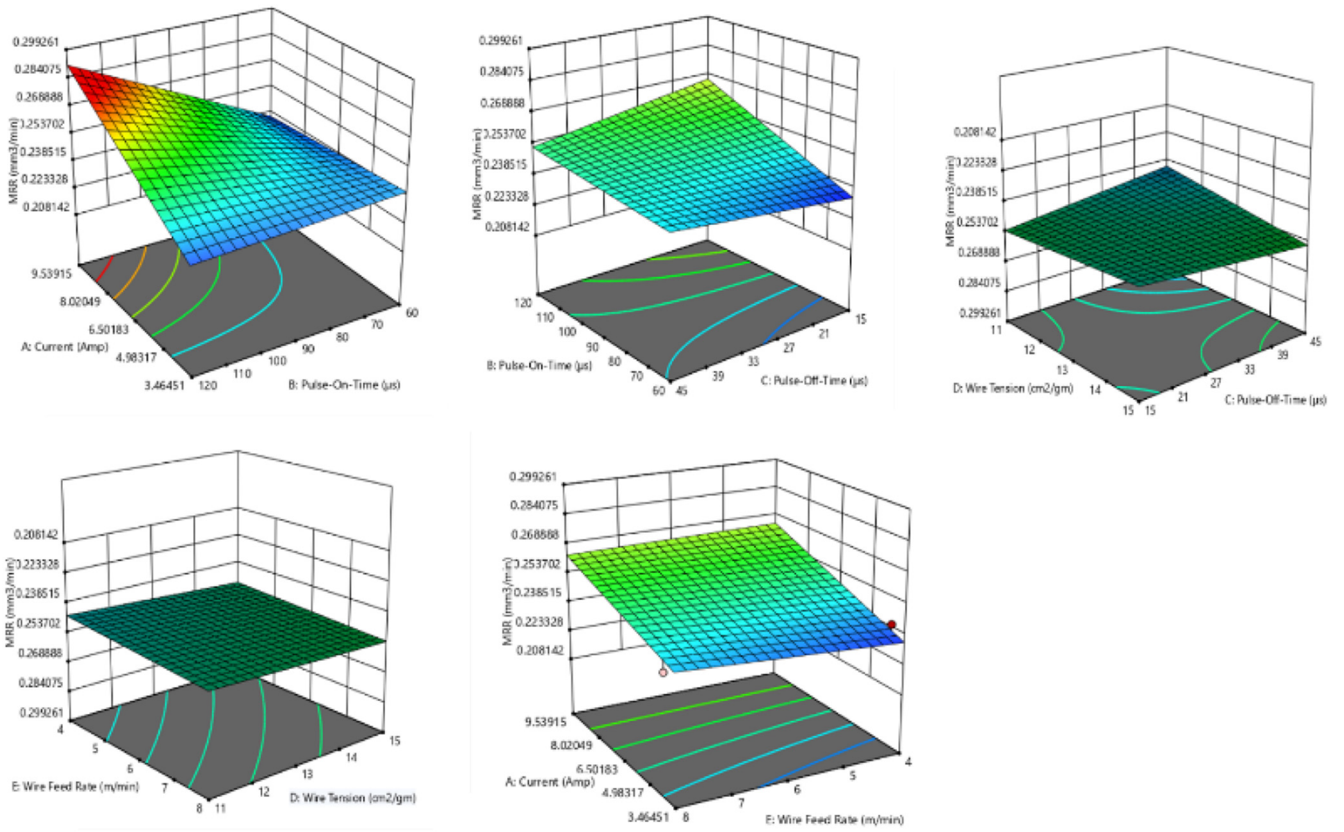

Fig. 6. 3D plots of MRR with different interactions (AB, BC, CD, DE & AE).

Table 3
ANOVA table for MRR.

Source	Sum of Squares	df	Mean Square	F-value	P-value
Model	0.0044	10	0.0004	17.73	< 0.0001
Current	0.0005	1	0.0005	21.65	0.0003
Pulse on time	0.0018	1	0.0018	73.35	< 0.0001
Pulse off time	0.0000	1	0.0000	0.1670	0.6882
Wire tension	0.0000	1	0.0000	0.8801	0.3621
Wire feed rate	0.0001	1	0.0001	2.82	0.1128
AB	0.0002	1	0.0002	6.62	0.0205
AE	0.0000	1	0.0000	0.9518	0.3438
BC	0.0002	1	0.0002	6.58	0.0208
CD	0.0002	1	0.0002	6.28	0.0233
DE	0.0000	1	0.0000	0.0616	0.8071
Residual	0.0004	16	0.0000		
Total	0.0048	26			

considered as machining parameter to analyse the material removal rate and surface roughness.

Magabe et al. (2019) examined the design of experiment methodology to develop an algorithm to identify the optimum value for Wire EDM machining technique. The machining features such as MRR and SR were measured based on process parameters. The WEDM machining of $Ni_{55.8}Ti$ was performed to develop a non-dominated sorting genetic algorithm (NSGA) II. The researcher found that Wire EDM of $Ni_{55.8}Ti$ alloy showed the improvement in surface quality (Rz,6.20 µm) and productivity (mrr,0.021 g/min). The surface defects were also studied by the researchers.

There are various parameters that affect the machinability of WEDM process. These parameters can be controlled by the proper selection of input parameter and optimization techniques. The ANN technique develops a mathematical model between input parameters and output parameters. There are number of input process parameters in wire EDM that affects the performance of the result (Padhi et al., 2014; Singh and Misra, 2019). In present study five input parameters are considered as training vector to develop the model between the input and output parameters by using ANN technique. Albeit many studies have been carried out in the past and reported in literatures on WEDM of NiTi SMA, but very few scholarly works have been carried out in regards of machining performance. The fabrication of slot in shape memory alloy is difficult task due to its strain hardening effect. This research focuses on WEDM machining of $Ni_{49}Ti_{51}$ SMA to explore the effect of process parameter over the material removal rate and to optimize the machining parameter to obtain the maximum material removal rate through RSM methodology and ANN approach. ANN tool box of MATLAB is utilized to develop the BPNN model. The effect of machined surface such as, recast layer formation, distribution of craters on machine surface and deviation of machined slot dimension were also investigated.

2. Experimental details

For the current research work, the experiments were performed on WEDM (Electronica Spring cut 734) machine. Five input parameters i.e. pulse-on-time, pulse-off-time, current, wire feed rate, wire tension were taken in account, the ranges for these were set according to machine limitations. The variation of these parameters on the material removal rate was investigated. A square workpiece of 100mmx100mmx6mm was taken for machining. The surface of the samples was grinded using a grinder-polisher machine ((Handimet 2, Buehler, China)) to measure the hardness of material. Fig. 1 presents the hardness measurement of the specimen. The samples were grinded with grit size of 400 in vertical and 600 in horizontal direction. Vicker microhardness (HV) measurements using a microhardness tester (Wilson Tukon™ 1202, China) with 1 kg load and dwell time of 15 s were conducted according to DIN EN ISO 18,265 standard. Five microhardness measurements for three different samples were taken and the average was calculated. The observed average value of the specimen was 129 by the vicker hardness (HV). The material removal rate was measured in mm^3/min by using the following formula:

$$\mathrm{MRR} = \frac{d \times l \times h}{t}\,\mathrm{mm}^3/\mathrm{min} \tag{1}$$

where t is the machining time, h is the height of the workpiece and l is the length of the cut and d is the kerf width. MRR was calculated in mm^3/min. Table 1 shows the process parameters used and their respective ranges.

Fig. 2 shows the dimensions of the fabricated slot by the WEDM process. The specimens were measured with an optical microscope (AM4815T, Dino-lite, Taiwan) with 30x magnification and DinoCapture 2.0 image analysis software. Five readings at random point are measured and the average was calculated. The measured average value of the machined slot is 2.42 mm. The measurement was repeated for three different samples.

Fig. 3 shows the methodology for the wire EDM process. The flow chart was prepared to present the flow of work of the present study. Fig. 4 presents the tasks performed for the machining of the specimen and shows different stages of the experimental methodology. The final machined slot was also presented.

3. Result and discussions

The Table 2 shows the value of the process parameters and material removal rate predicted by ANN model and RSM model.

3.1. Analysis by RSM

Fig. 5 shows the analysed result on the MRR by the input process parameters (peak current, pulse on time, pulse off time, wire tension and wire feed) and desirability index ramp graphs and bar graphs and the maximum desirability that is achieved for the

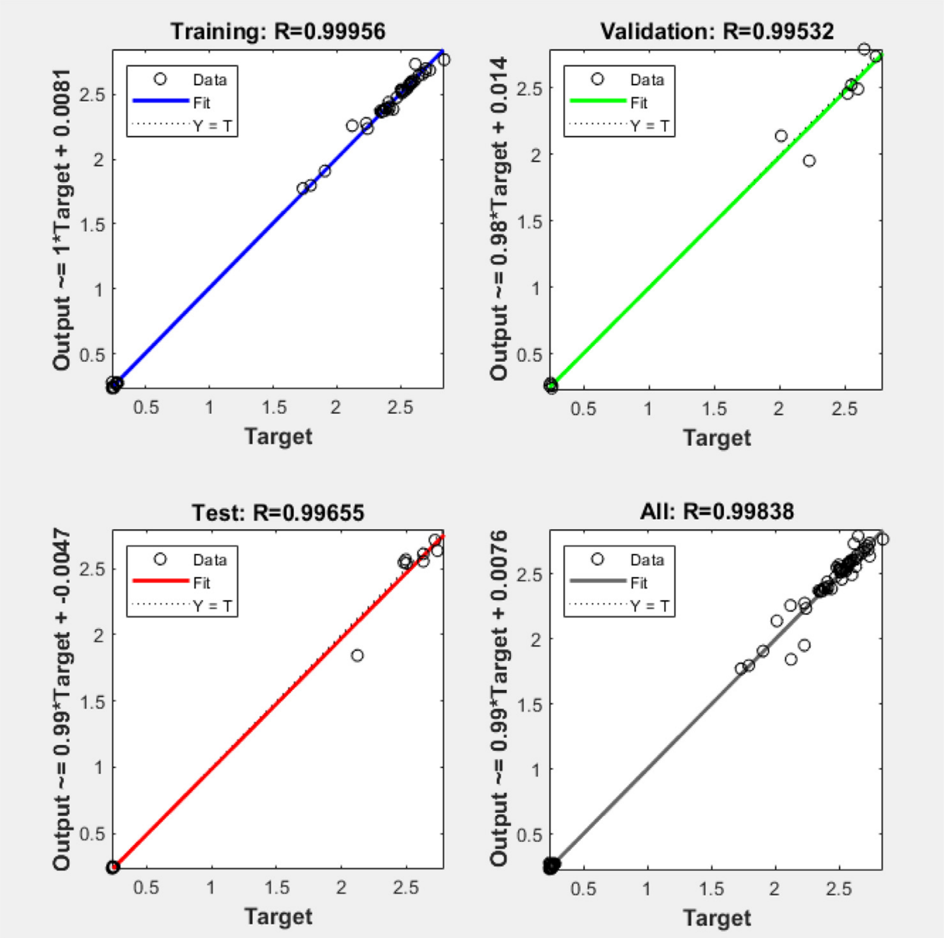

Fig. 7. Linear regression analysis for experimental and ANN predicted values.

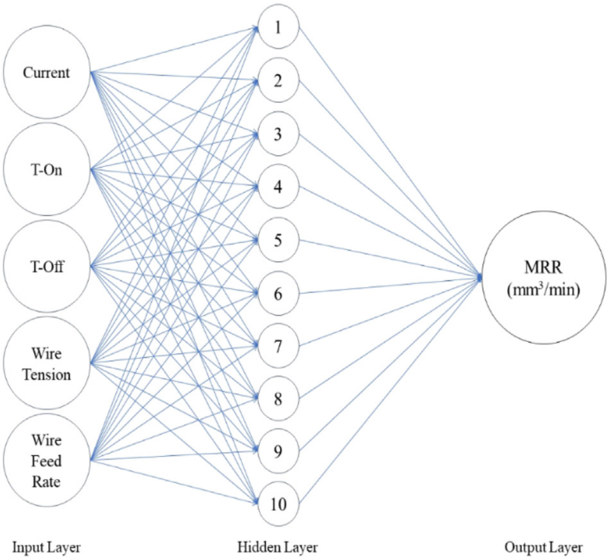

Fig. 8. BPNN model for MRR.

response. The best conditions and comparable results for this desirability are -: $I_p = 8$ Amp, Ton = 120 µs, Toff = 17 µs, WT = 14 cm^2/gm, WF = 7 m/min and the obtained MRR is 0.3 mm^3/min.

Fig. 6 presents the 3D plots of MRR with different interactions (AB, BC, CD, DE & AE). It is found that the MRR increases as there is increase in the current or pulse on time. MRR increases with increase in I.P. regardless the increase in Ton but maximum MRR is achieved at peak value of both I.P. and Ton. This is because, higher the discharge energy (i.e. I.P. * Ton) more powerful the spark at the junction creating higher temperature and causing more material to melt and erode hence higher the MRR. MRR increases with decrease in Toff hence max MRR is achieved when the Ton is max, and Toff is minimum. Wire Tension and Wire feed do not much influence MRR. Table 3 shows the ANOVA results of MRR. The p-value less than 0.0500 show that the model terms are significant with 95% certainty. Accordingly, I.P., Ton, interaction effect of I.P. xTon, Ton xToff, Toff xWT have significant effects on MRR. The rest of the terms having value more than 0.0500 are not significant for the present work. Equation 6 shows the resultant regression equation obtained for MRR.

3.2. ANOVA For MRR

3.3. Regression equation

MRR = 0.268165 + −0.00832798 * Current + −0.000218757 * Pulse-On-Time + −0.000862434 * Pulse-Off-Time + −0.00315575 * Wire Tension + 0.00426597 * Wire Feed Rate + 0.000162063 * Current * Pulse-On-Time + −0.000352083 * Current * Wire Feed Rate + 1.39048e−05 * Pulse-On-Time * Pulse-Off-Time + 0.000157937 * Pulse-Off-Time * Wire Tension + −8.95833e−05 * Wire Tension * Wire Feed Rate (6).

3.4. Analysis by ANN

Fig. 7 represents a correlation between experimental and ANN predicted results. The three plots represent training, validation, testing data. The fourth plot shows a combination of the combined three data. The R value indicate the relationship between the results, as close as the R value is to 1 the better is the linear relationship between the results. The R values of training and validation are 0.99956 and 0.99532 respectively, closer to 1 affirming a strong interrelationship between the input and output. Thereby establishing a strong understanding between experimental values and ANN predicted values. The optimum structure of artificial neural network model was selected by trial and error by varying the neurons in hidden layer. The model developed is a feed forward BPNN with having 5 process parameters with 10 hidden layer

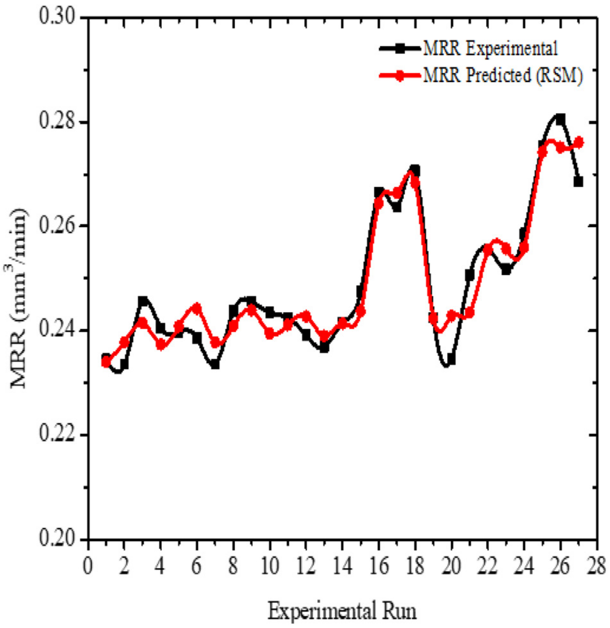

Fig. 9. Comparison between experimental versus predicted values.

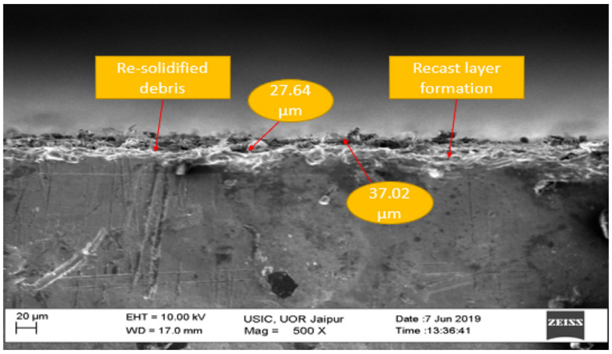

Fig. 10. Formation of recast layer and re solidified particles on the surface.

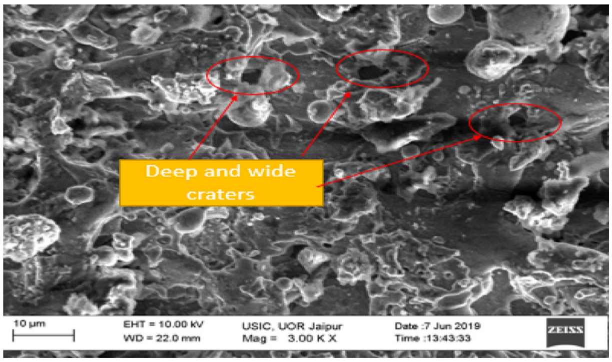

Fig. 11. Microstructure of machine slit of WEDM surface (deep and wide craters).

and 1 response. So, 5-10-1 is the most suitable network for current work as shown in Fig. 8. In addition, the experimental data was compared with RSM predicted results as shown in Fig. 9.

3.5. Material characterization

Fig. 10 shows the deep and wide crater on the surface of machined materials. It revealed that at the high discharge energy the material removal is more by which the deep and wide craters are obtained on the surface. Since Wire EDM uses thermal energy, the machining zone of the material involves high temperature difference due to rapid heating and quenching effect from the dielectric fluid. As a result of this the melted material gets re-solidifies on the outer surface of the specimen. This re-solidified layer is known as the recast layer (Shandilya et al., 2018). Figure no. 11 presents the formation of the recast layer on the machined surface in the present experimental work. The size of 26.44 μm and 27.91 μm size recast layer thickness is obtained which is shown in the Fig. 11. It is observed that the thickness of recast layer increased with the increase in discharge energy, that results in melting of material and a layer of debris recast on the specimen.

4. Conclusion

In the present experimental investigation, modelling and optimization of WEDM process is done for shape memory alloy by box-behnken design (BBD) and artificial neural network (ANN) approach to analyse the material removal rate. The obtained optimal solutions were correlated with the validated tests. The ANN model predicted the result with high accuracy. Also, the results of the BPNN predicted model were compared with the experimental results. The following conclusions are obtained.

1. It is found that the Ton and I.P are the most significant factors contributing towards MRR. As the discharge energy increases the MRR also increases.
2. The ANN model is effectively established for prediction of material removal rate in WEDM of NiTi shape memory alloy.
3. The material characterization revealed that the formation of recast layer, thickness 26.44 μm and 27.91 μm are obtained on the machined surface area. The deep and wide craters are also observed during machining by the high discharge energy.
4. The comparison between the experimental values and the predicted values lies within the given range of the parameters.
5. The proposed process model is perfectly suitable for the engineers to optimise the machining parameters of wire EDM.
6. Similar approach can be utilized to study the effect of wire EDM parameters on other responses such as surface roughness, dimensional deviation, kerf width, overcut etc. on different materials.

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Conflict of interest

The author declares that there is no conflict of interest.

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