SPECIAL ISSUE ARTICLE
INNOVATION AND EMERGING TECHNOLOGIES

Fatigue analysis of electro discharge machined Nitinol 60

Mahendra U Gaikwad [1,*], Pradeep Gaikwad [2], Krishnamoorthy A [3], Vijaykumar S Jatti [4], Nitin Ambhore [5], Ankit D. Oza [6], Manoj Kumar [7], Manish Gupta [8] & Unnati Joshi [9]

Nitinol 60 (NiTi60) is a shape memory alloy (SMA) where the atomic percentage of nickel is slightly higher than titanium. It advantages the material to have higher hardness and better sensitivity to phase transformation. One of the machining techniques that is preferred to cut hard material is electrical discharge machining (EDM). This study aims to examine the fatigue characteristics of a NiTi60 alloy that has undergone electro-discharge machining and examine the impact of machining parameters on microstructural changes. In this investigation first, the influence of EDM process parameters such as pulse current, voltage, pulse on time, and pulse off time on surface integrity aspects was investigated. Second, the impact of these process variables on fatigue strength was examined. The surface integrity parameters of EDM-machined specimens, such as microcracks, surface crack density (SCD), white layer thickness (WLT), and residual stress formation have been examined by various characterization techniques. The obtained results show that pulse current and voltage are dominating factors affecting SCD. The thickness of the white layer seems to be increased with the rise in the pulse current and pulse on time, and tensile kinds of residual stresses are present in the WLT region, whose magnitude is dependent on process parameters. The fatigue tests were performed using a servo hydraulic testing machine at a frequency of 20 Hz for 106 number of cycles. The fatigue crack initiation, propagation, and effects of process parameters have been examined. It has been found that an increase in pulse current and voltage leads to the generation of microvoids in the WLT region and thereby causes fatigue cracks to take birth. Later on, a correlation between WLT and SCD was observed by implementing an artificial neural network (ANN) model. The accuracy of ANN model prediction is reported to be high, where WLT and SCD have a 0.98 observed correlation coefficient.

***Keywords*: Fatigue Analysis; Surface Crack; Microcracks; EDM, Shape Memory Alloy.**

Innov. Emerg. Technol. 2023.10. Downloaded from www.worldscientific.com
by Joy Quek on 12/17/23. Re-use and distribution is strictly not permitted, except for Open Access articles.

INTRODUCTION

Recently developed materials, namely nickel–titanium Tinol 60, have outstanding material properties, including high hardness; therefore, these materials are difficult to process using conventional machining processes. Electrical discharge machining (EDM) is one of the practical solution methods for processing hard materials[1–5]. The mechanical properties of parts after EDM machining worsen due to change in surface roughness (SR), surface morphology, formation of surface cracks, the white layer, and the heat-affected zone, and these initiate crack and fracture under various fatigue loads[6–12]. The shape-memory effect and super elasticity are two of the NiTi alloy's standout properties, making it a member of the Smart Material Alloy (SMA) family of materials[13]. SMA found useful in various sectors, including aerospace, biomedical implants, sensor and actuators, miniature grippers, and dental applications[13]. Smart materials are very sensitive to mechanical loads and operating conditions, which are difficult to machine through traditional machining processes[14]. Also, machining such material to obtain a good surface finish with bulk material removal is a challenging task[14]. Hence, it has been advised by researchers to choose nonconventional machining processes such as EDM, wire EDM, abrasive water jet cutting, and electrochemical machining[15,16]. Machining of the NiTi60 alloy with an EDM machining process, and investigating the surface integrity parameters attracts the attention of researchers. Surface integrity is related to surface topology, residual stresses, roughness, hardness, phase transformation, and microstructural changes.

[1,2]Department of Mechanical Engineering, JSPM, Narhe Technical Campus, Savitribai Phule Pune University, Pune, India (mahendragaikwada1@gmail.com, pradeepgaikwad9226@gmail.com), [3]Department of Mechanical Engineering, Sathyabama Institute of Science and Technology, Chennai, India (akrish61@gmail.com), [4]Symbiosis Institute of Technology, Symbiosis International (Deemed University) Pune, India (vijaykjatti@gmail.com), [5]Department of Mechanical Engineering, Vishwakarma Institute of Information Technology, SPPU, Pune, India (nitin.ambhore@viit.ac.in), [6]Department of Mechanical Engineering, Parul University, Vadodara, Gujarat 391760, India (ankitoza6060@yahoo.in), [7]Department of Mechanical Engineering, ABES Engineering College, Ghaziabad, Uttar Pradesh, India (mky2011@gmail.com), [8]Division of Research and Development, Lovely Professional University, Phagwara, Punjab, India (gupta.manishlpu@gmail.com), [9]Parul Institute of Engineering and Technology, Parul University, Vadodara, Gujarat 391760, India (unnatiajoshi@gmail.com). *Correspondence should be addressed to: M.U.G. (mahendragaikwada1@gmail.com)

Received 22 August 2023; accepted 16 October 2023; published online 13 December 2023; doi:10.1142/S2737599423400091

This article is part of the "Special Issue on Innovative and Emerging Advanced Manufacturing Technologies", edited by Chander Prakash (*Lovely Professional University, India*), Alokesh Pramanik (*Curtin University, Australia*), Mohammad Khalid (*Sunway University, Malaysia*) & Shankar Sehgal (*Panjab University, India*).

© World Scientific Publishing Co.

Innov. Emerg. Technol. 2023.10. Downloaded from www.worldscientific.com by Joy Quek on 12/17/23. Re-use and distribution is strictly not permitted, except for Open Access articles.

These parameters help to judge the quality of machined surfaces[17]. Haci Ozerkan *et al.*[18] reported the theoretical method for fatigue strength evaluation. They found that fatigue life improved from 1.2% to 8.5% by improving SR with a decrease in input current and pulse on time. This is because polarity change has a greater effect on fatigue life, which makes the machined surface free from cracks. Chin *et al.*[19] conducted experiments to examine how the discharge current of the EDM process affects the fatigue life and surface hardness of the aluminum 6061 alloy. They reported that an increase in current increases the white layer thickness (WLT) from 10.31 to 19.38 µm, this gives rise to fatigue crack initiation and hence to be consider as a serious factor. Shahid Mehmood *et al.*[20] the fatigue limit of the Al 2024 T6 is investigated for discharge current values of 3, 6, 9, and 12 A discharge current values while all other parameters were kept constant. They reported that at the discharge current value of 12 A, the fatigue limit was only one-half the fatigue limit of the conventionally machined specimens, but at 3 A current compared to 12 A can improve the fatigue limit by up to 10%. Also stated that no single surface integrity parameter like SR, hardness, WLT can determine the fatigue strength of aluminum alloy 2024 T6. Ozerkan *et al.*[21] investigated AISI 8740 alloy steel to estimate fatigue strength. The finding revealed that SR increases with increasing current and pulse duration along with decreasing fatigue strength of the material. Chahardehi *et al.*[22] conducted an extensive review of the existing empirical formulae based on R-ratio. Mahendra Gaikwad *et al.*[23] investigated the influence of EDM parameters on the fatigue strength of titanium grade-2 material, they reported an increase in current and Pon causing earlier fatigue failure of EDM machined specimens causing a reduction in the fatigue strength of the material. It also stated that the maximum fatigue strength evaluated at 106 cycles was 397.88 MPa, which is less than the ultimate strength of a 465 MPa workpiece. Many researchers are working in the area of surface integrity. Surface perfection is the most important parameter regarding SR, topography, surface hardness, residual stress, phase transformation and microstructural changes, and quantifies part quality. Surface integrity is related to SR, surface morphology, surface hardness, and so on, which are closely related to surface quality and part performance. Different researchers have contributed their efforts in experimental analysis of each of these surface integrity parameters during the EDM machining of various materials[12,24–29]. Today, artificial neural network (ANN) is gaining considerable attention of researcher working in manufacturing areas, as it is an alternative to the statistical method. Also, it offers the advantage of giving the solution without specifying the relationships or the form of relationships between the input and output variables[30]. In association with this, Joshi *et al.*[31] reported that the radial basis function neural network is fast and easy to configure, but the feed forward back propagation neural network provides a more accurate process model. Sathyabalan *et al.*[32] employed a feed forward, multilayer perception neural network with a single hidden layer to predict the sliding wear loss and hardness of fly ash and SiC-reinforced aluminum alloy. The machining of hard materials such as nitinol and the evaluation of surface integrity parameters have attracted the attention of researchers. It is with this intention that this research activity was carried out. Initially, the effect of EDM process parameters such as pulse current, voltage, pulse on time, and pulse off time on surface integrity aspects were investigated. And lastly, the influence of these process parameters on fatigue strength was investigated along with fatigue crack initiation and propagation also ANN model was used to understand the correlation between experimental and regression model analysis.

MATERIAL AND METHODS

NiTi 60 alloy in 80*25*4 mm dimension was purchased from Nextgen Steels and Alloys, Mumbai, India. The mechanical properties as received from the supplier are a yield strength of 185 MPa and an ultimate tensile strength of 735 MPa. Most engineering parts encounter cyclic loading, reversed loading or repeated loading and hence fatigue analysis is required to be done before any product is launched or put into operation. Having this in mind, this research is planned to conduct fatigue analysis on electro-discharge machined samples and to investigate the effect of machining parameters on fatigue properties. Machining parameters such as electro-discharge voltage, pulse current, pulse on time, and pulse off time were varied as shown in **Table 1** to prepare dog bone samples as per the ASTM E466 standard (**Figs. 1 and 2a**). All samples were machined through a die sink EDM machine (Model: Electronica Elektra) with a copper electrode of 20*20 mm (**Fig. 2b, c**).

Table 1 EDM process parameters used in experiments.

Parameter	Level 1	Level 2	Level 3
Electro-discharge voltage (v)	40	55	80
Pulse current (A)	4	6	8
Pulse on time (µs)	20	40	60
Pulse off time (µs)	5	7	9

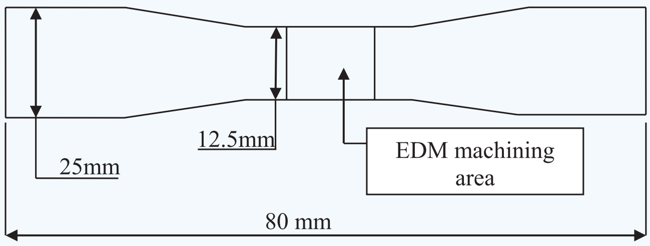

Figure 1 EDM-machined fatigue specimen.

Tensile tests were initially conducted at Inston (Servo-hydraulic test), where the ultimate tensile strength was found to be 903.43 MPa and the yield strength was found to be 275.75 MPa for all samples. Fatigue tests were then conducted at 20 Hz, and the stress ratio was 0.5. Tests were conducted for high fatigue cycles (10^{6}) by the axial direct stress fatigue method. The mean load of 5,000 N, maximum load of 6,450 N, and minimum load of 3,550 N were maintained during the fatigue test. Microstructure characterization was done using scanning electron microscopy (JEOL JSM 6360a) for the EDM machined area as shown in **Fig. 1**, with the purpose of investigating the formation of WLT and cracks. As WLT was likely to be observed in SEM analysis, there is further need to understand the grain orientation in WLT that was observed by the electron backscatter diffraction (EBSD) technique for the EDM machining area, as shown in **Fig. 1**. The SEM technique requires less time for sample preparation and microscopic observations due to which it has been implemented in the current investigations. As EDM is concerned with sudden heating and cooling processes, metallurgical changes are likely to take place in the EDM machining area. This can be evaluated by the XRD analysis test as shown in **Fig. 5**.

RESULTS AND DISCUSSION

Microstructure of NiTi 60 alloy and electro-discharge machined sample

Fatigue performance depends on the surface integrity parameters since fatigue cracks typically begin on free surfaces[33]. Surface integrity parameters such as SR, WLT, residual stress, and heat-affected zone

© World Scientific Publishing Co.

Innov. Emerg. Technol. 2023.10. Downloaded from www.worldscientific.com
by Joy Quek on 12/17/23. Re-use and distribution is strictly not permitted, except for Open Access articles.

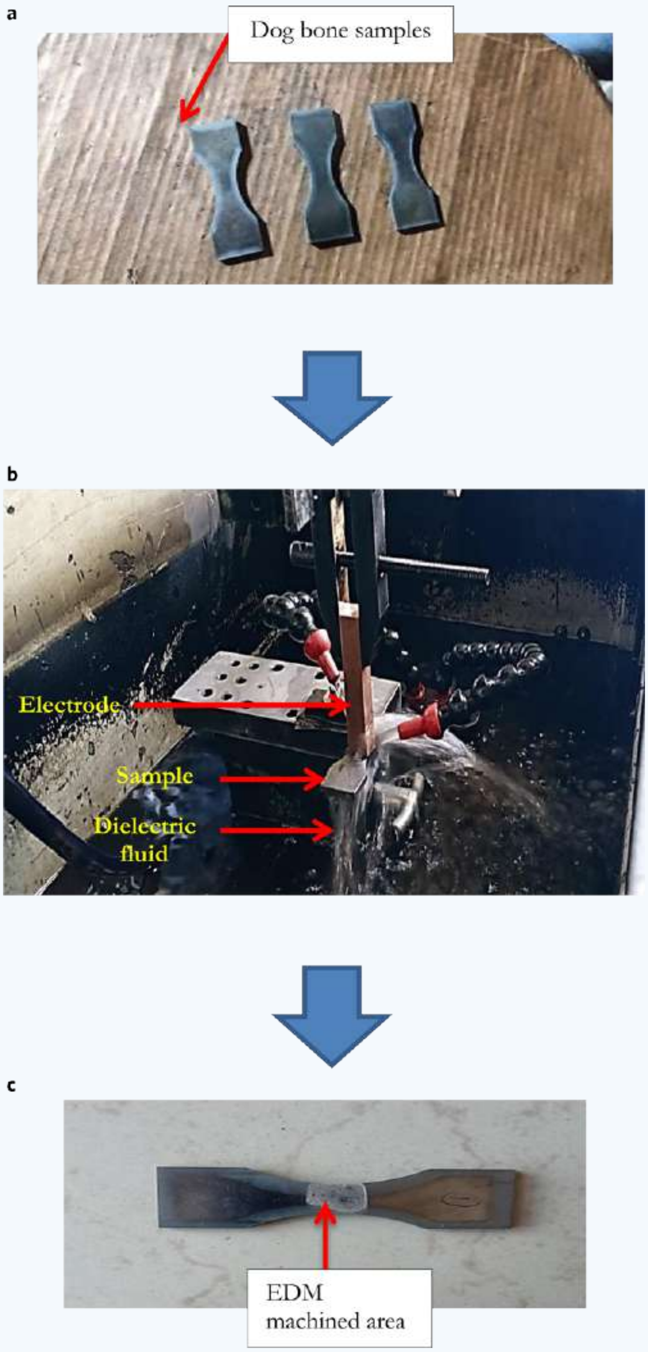

Figure 2 (**a**) Sample before machining. (**b**) Sample during EDM machining. (**c**) Sample after machining.

are related to electro-discharge machined surfaces[34]. Low SR, a few surface defects and high compressive residual stresses are beneficial to fatigue performance[33]. In order to investigate the effect of surface integrity parameters on fatigue performance, an attempt has been made to understand the micro-structure changes observed on the various samples before and after electro-discharge machining. **Figure 3a** shows the un-machined or before machining microstructure condition where the surfaces are free from microcracks, and **Fig. 3b** shows machined or after machining microstructure condition of samples where the formation of microcracks is observed by using the SEM characterization technique.

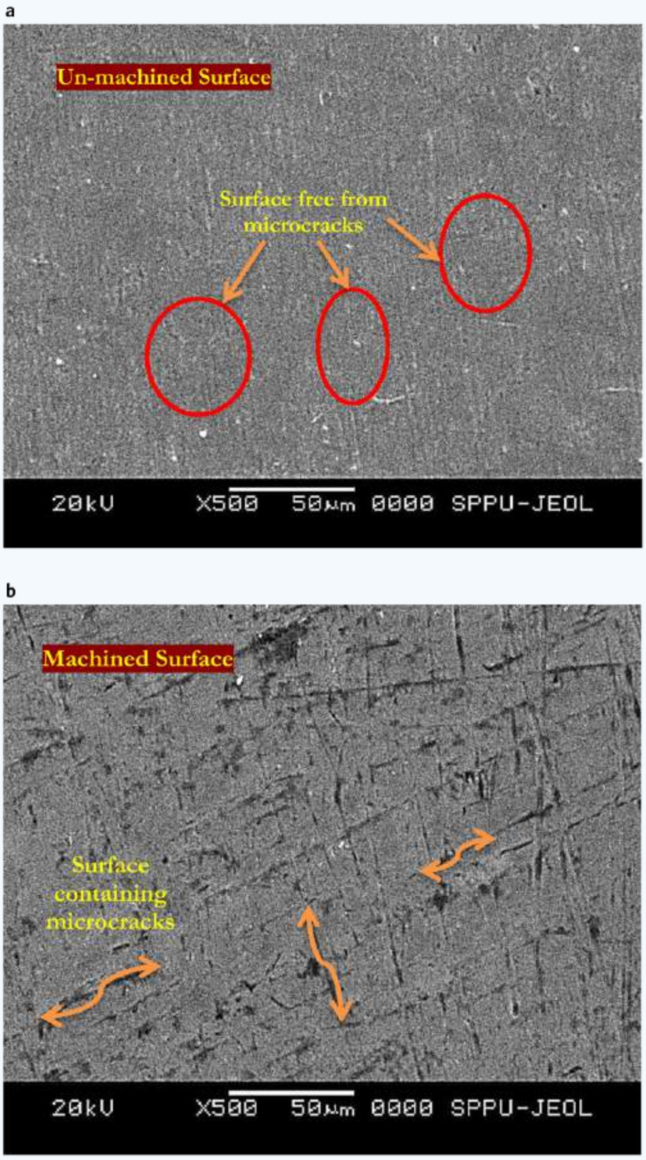

Figure 3 (**a**) The microstructure of NiTi60 before machining. (**b**) The microstructure of NiTi 60 after machining with pulse current 4A and pulse on duration 20 µs.

Earlier, similar investigation for microcrack evaluation was been reported during the EDM machining process, where the SEM characterization technique seems to be one of important and promising technique[35–39]. Electro-discharge machining is considered to be a thermo-mechanical process where the component is subjected to a sudden heating and cooling process[34]. The formation of a few microcracks begins at the end of a low value of pulse current and pulse duration because these microcracks lead to the tensile residual stress induced by the rapid quenching[40,41]. The formation of such microcracks on machined surfaces is not beneficial for fatigue performance; hence, they need to be further investigated in terms of their surface crack density (SCD), as discussed in the next section.

Surface crack density assessment

Crack formation is related to the EDM parameters, especially pulse current, and pulse on time[42]. In corresponds to this, the effects of variation in pulse current and pulse on duration have been investigated. Micro

© World Scientific Publishing Co.

Innov. Emerg. Technol. 2023.10. Downloaded from www.worldscientific.com
by Joy Quek on 12/17/23. Re-use and distribution is strictly not permitted, except for Open Access articles.

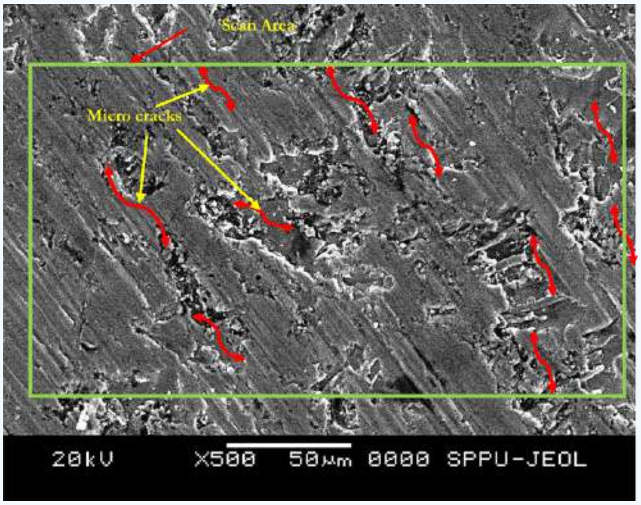

Figure 4 Microcracks evaluation through SEM for pulse current 8A and pulse on duration 60 µs.

cracks were not observed at 4A and 20 µs but at 8A and 60 µs micro cracks were visible. The SCD was measured with the help of Image J software by importing the SEM images of machined surfaces as shown in **Fig. 4**. The SCD was measured using Equation (1) while the WLT was measured by the SEM technique as shown in **Fig. 2**[43].

$$\text{SCD} = \text{Total Crack Length/Image Area} \ldots (1)$$

The SCD is a maximum 0.0382 for trial number 9 and a minimum 0.056 for trial number 4 as shown in **Table 2**. For SCD, the pulse current and voltage process parameters seem to be dominating factors in electro-discharge machining. For maximum values of SCD, the WLT was ranging from 10 to 16 µm and for minimum values of SCD, the WLT was ranging from 6 to 10 µm, as shown in **Table 2**. The obtained results are similar to the previous studies conducted by Roy *et al.*[43], Mohanty *et al.*[44] for determining WLT and SCD during EDM machining of Nitinol and Ti alloy. Also interesting to know that pulse current and voltage are dominating factors affecting SCD as shown in **Fig. 5**. Whereas WLT seems to be increased with the rise in the pulse current and pulse on time, which can be evident from **Table 2**.

Recast layer thickness assessment

To investigate the grain orientation in WLT EBSD technique is used. **Figure 6** shows the inverse pole figure (IPF) for EDMed machined cross sections, where the WLT is identified by a violet-colored layer of smaller grain size (less than 1 *µ*m) than that of the parent material. Also, several black-colored regions embedded in the WLT indicate the microvoids and cracks formed due to the rapid quenching during EDM machining. The fatigue crack will be promoted due to the presence of such cracks and voids in the WLT[45]. Similar studies were conducted by Fu *et al.*[46] where they observed microvoids in the region of WLT during wire EDM machining of shape memory alloy[46].

Table 2 Process parameter along with WLT and SCD.

Runs	Vtg	Crt	Pon	Poff	WLT	SCD
1	40	4	20	5	7	0.0068
2	40	6	40	7	8	0.0101
3	40	8	60	9	10	0.0210
4	55	4	40	9	7	0.0056
5	55	6	60	5	12	0.0221
6	55	8	20	7	16	0.0310
7	80	4	60	7	11	0.0099
8	80	6	20	9	6	0.0298
9	80	8	40	5	10	0.0382

Residual stress assessment

The fatigue life of EDMed specimens is also significantly influenced by residual stress created on the machined specimens[16]. Metallurgical changes are likely to be observed during EDM Machining as it is one of the sudden heating and cooling processes. Due to this fact, the heat transfer rate becomes non-uniform, resulting in the production of residual stresses on the machined surface. Based on the earlier studies,[47] it has been noticed that tensile kinds of residual stresses are present on EDM-machined surfaces. However, the magnitude of these tensile residual stresses is dependent on EDM input parameters, especially pulse current and voltage[42]. **Figure 7a** shows an XRD plot for residual stress occurring for a pulse current of 6 A and a voltage of 55 V, while **Fig. 7b** shows an XRD plot for residual stress occurring for high values of a pulse current of 8 A and a voltage of 80 V. The residual stresses noted for a higher value of current were 155.7 MPa, such formation of residual stresses on the EDMed machined surfaces will exceed the fracture strength of the workpiece material by the generation of cracks and hence to be avoided[44]. Such a similar investigation was conducted by Liu *et al.*[16] and found that

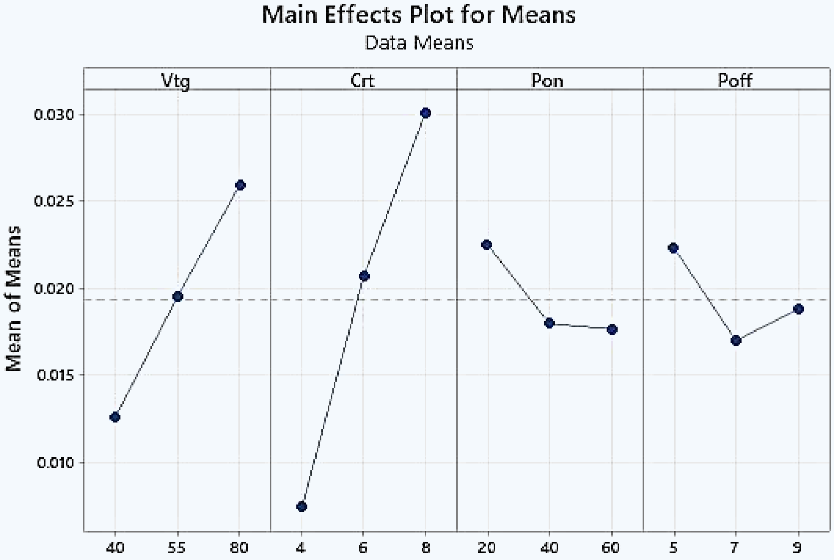

Figure 5 Main effect plot of SCD.

© World Scientific Publishing Co.

Innov. Emerg. Technol. 2023.10. Downloaded from www.worldscientific.com
by Joy Quek on 12/17/23. Re-use and distribution is strictly not permitted, except for Open Access articles.

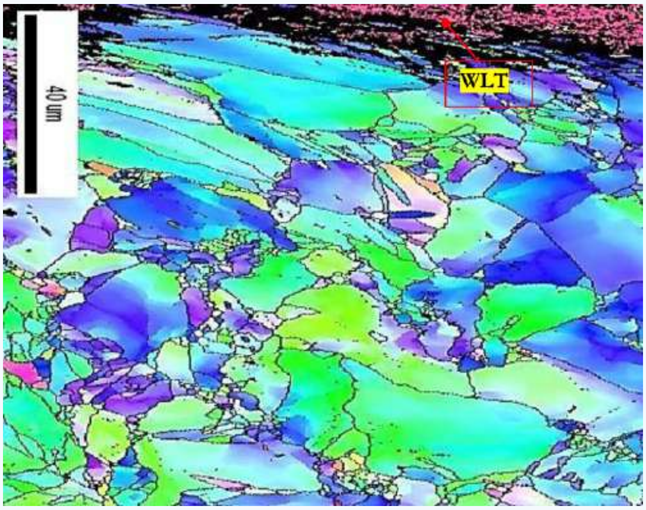

Figure 6 WLT analysis by EBSD technique.

fatigue cracks were initiated by microvoids in the thick white layer, and were facilitated by high tensile residual stress developed during wireEDM machining of shape memory alloy. Migration of electrode copper material on the machined surface (Nic & Tic) can be evident from the XRD plot shown in **Fig. 5** and the presence of oxide layers (Nio & Tio) due to the electro-thermal nature of material removal that may be composed of micro cracks can also be evident.

Fatigue crack initiation and propagation assessment

There are three distinct phases of fatigue failure: (a) early crack nucleation and minor crack growth; (b) extended crack growth; and (c) quick final failure[48]. The loss in fatigue life of the EDM specimen is thought to be caused by surface imperfections, a high propensity for the recast layer to crack, and significant surface tensile residual stresses[49,50]. The recast layer is brittle in nature and contains cracks. Therefore, the cracks can propagate easily; the longer cracks accelerate the fracture process. The cracks in the recast layer and the brittle nature of the recast layer stimulate crack propagation. Also, the machining parameters affect the nature of the recast layer and the heat affected zone[50]. SEM examination of fatigue-tested specimens was carried out as shown in **Fig. 8** below. It is observed that an increase in current during the EDM machining process causes thick WLT to develop by giving rise to generate microcracks networks in the WLT or subsurface area. These microcracks propagate from the subsurface to the work surface called as fatigue crack propagation phase. The crack networks generated on the machined specimens remain in the tensile residual stress field, yielding to stress instability state that accelerates crack network propagation[51]. Hence, fatigue cracks originated from the microvoids in the thick WLT, which were facilitated by high tensile residual stress. Such a similar investigation was carried out by Lu Songsong *et al.*[52]. Where they reported the formation of a bunch of cracks on the subsurface area of the specimen and further propagation of these cracks to the main surface, thereby reducing the fatigue life of the aluminum alloy[52] and Liu [2018], they stated that crack initiation and propagation are the combined effects of high tensile residual stress and thick WLT during Wire EDM machining of shape memory alloy[16]. Also, it is interesting to note that, during this investigation process, twin bands of fatigue cracks are likely to be observed near thick porous WLT during electro-discharge machining of NiTi 60 alloy. Such a similar investigation was reported by Liu *et al.*[46] where they observed groups of fatigue cracks containing twin bands, which may be due to stress concentration at the vicinity of the crack tip during wire EDM machining Nitinol smart material alloy[45]. To understand the effect of EDM process parameters on fatigue strength during machining hard materials, Mahendra Gaikwad *et al.*[23] conducted fatigue strength evaluation for EDM machining on titanium alloy and reported that increase in current and pulse-on time, the fatigue strength of titanium alloy decreases[53].

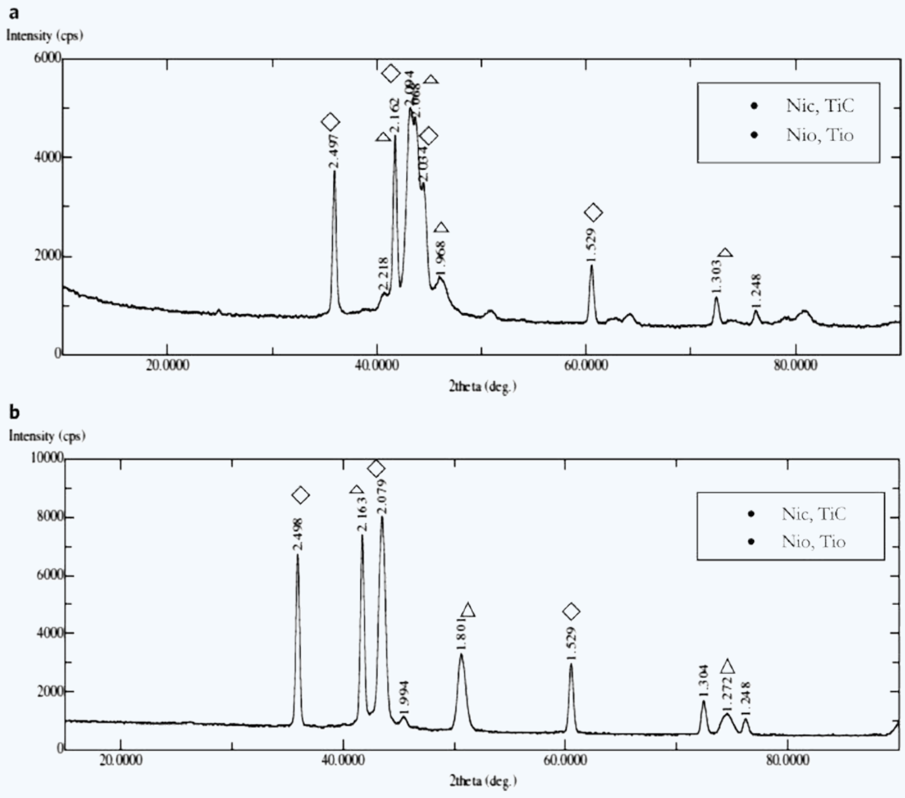

Figure 7 (**a**) XRD plot for NiTi 60 alloy.(**b**) XRD plot for NiTi 60 alloy.

ARTIFICIAL NEURAL NETWORK MODELING AND PREDICTION

The Taguchi L9 method of DoE is employed to acquire the experimental data. The ANN model is developed for WLT and SCD. The values obtained by the ANN model and regression model are compared with experimental values to decide the nearness of the predictions and actual values. Regression analysis

© World Scientific Publishing Co.

Innov. Emerg. Technol. 2023.10. Downloaded from www.worldscientific.com by Joy Quek on 12/17/23. Re-use and distribution is strictly not permitted, except for Open Access articles.

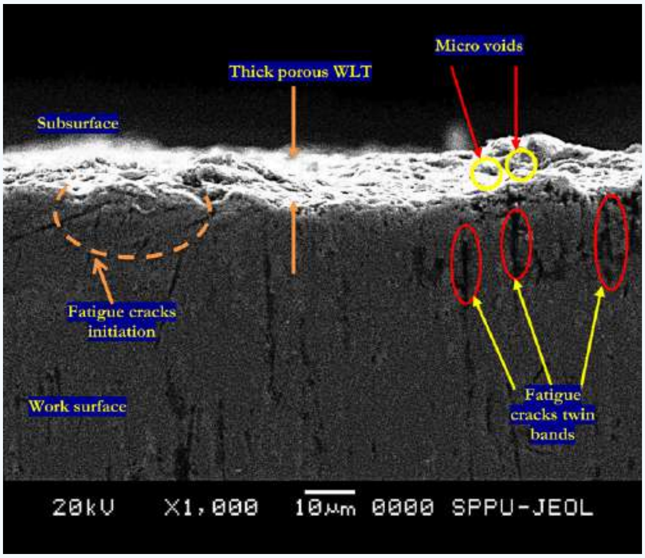

Figure 8 Fatigue crack propagation.

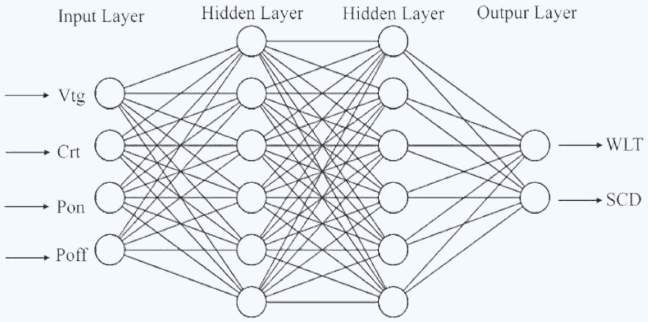

Figure 9 ANN architecture.

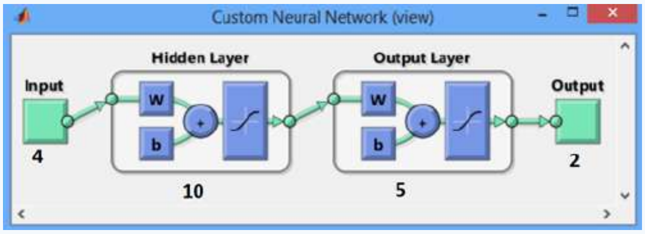

Figure 10 Neural network model.

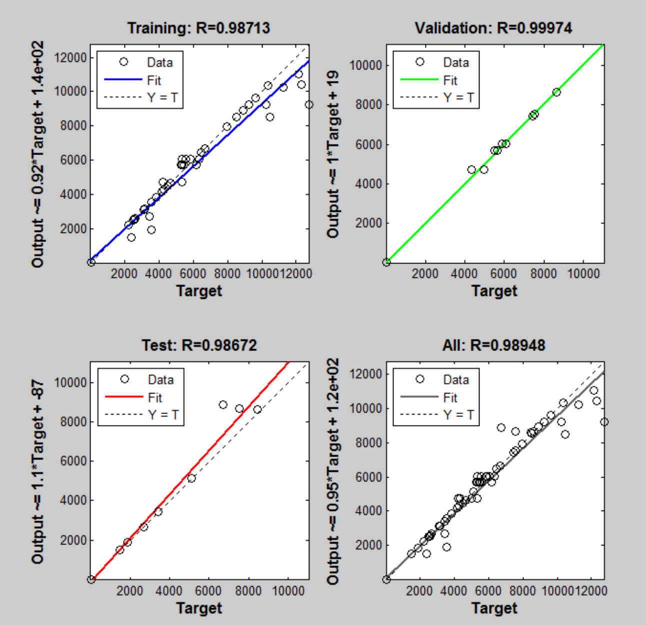

Figure 11 Regression plot for WLT.

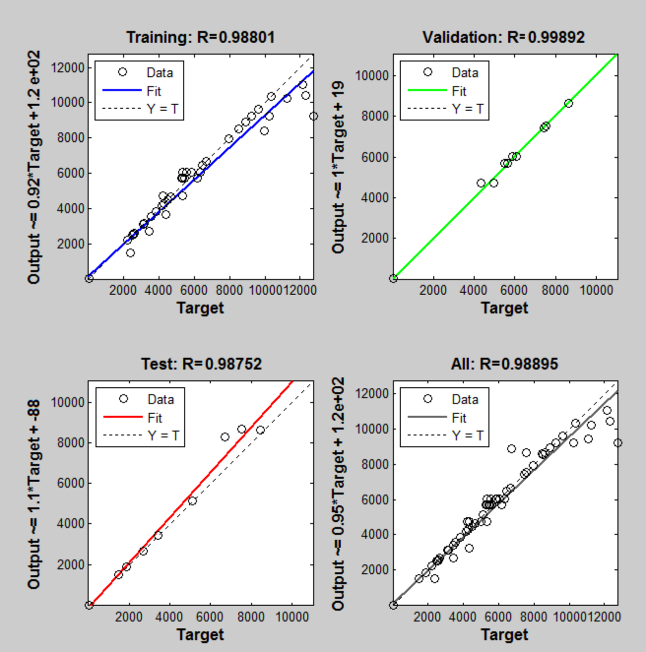

Figure 12 Regression plot for SCD.

helps to investigate the significant relationship exists between two or more variables on dependent variables. In this investigation, regression analysis of WLT has been investigated to understand the effect of EDM process parameters like current, voltage, pulse on time, and pulse off time. The Levenberg–Marquardt back propagation-based back propagation algorithm is employed[53]. There are two hidden layers and 10 neurons in the hidden layer with "tansigmoid" is used. The ANN architecture and model developed in MATLAB are depicted in **Figs. 9 and 10**.

© World Scientific Publishing Co.

Innov. Emerg. Technol. 2023.10. Downloaded from www.worldscientific.com by Joy Quek on 12/17/23. Re-use and distribution is strictly not permitted, except for Open Access articles.

In the ANN model, the performance parameter correlation coefficient value (R) for both the training and testing data output parameter is used to assess the network's performance. The regression plot for WLT and SCE is shown in **Figs. 11 and 12**, respectively. If the value of R is equal to 1, then there exists a very close relationship exists between them, zero means a random relationship, and greater than 0.9 means the quality is better[54]. The observed correlation coefficient between the WLT and SCD is 0.98. The correlation coefficient between the predictions of the ANN model and the results of the experiments is very near to 1, indicating that the ANN model predictions and the experimental findings agree very closely. Thus, the use of the ANN model advent in this analysis has led to the predication and validation of data and processes in a better way[55].

CONCLUSION

SEM techniques can be effectively used for the evaluation of microcracks, microvoids, SCD, and WLT during the machining of NiTi alloy. SCD can be regulated by maintaining pulse current and voltage. WLT can be regulated by maintaining pulse current and pulse on time, and tensile kinds of residual stresses are likely to be observed in the WLT zone, whose magnitude is dependent on machining process parameters. An investigation has also been done for fatigue crack initiation, propagation, and effects of process parameters, where it is observed that increment in pulse current and voltage leads to the formation of microvoids in the WLT region, and thereby causing fatigue cracks to born. WLT and SCD have a 0.98 observed correlation coefficient. Given that there is a high correlation between the predictions of the ANN model and the outcomes of the experiments, which is near 1, the accuracy of the ANN model predictions is high. Thus, use of an ANN model can be an effective method to correlate with the experimental results related to WLT and SCD evaluation during EDM machining of nitinol material.

CONFLICT OF INTEREST STATEMENT

The authors declare that; they have not received any financial or non- financial interest that are directly or indirectly related to the work submitted for publication.

ORCID

Mahendra U. Gaikwad https://orcid.org/0000-0003-2552-1518
Pradeep Gaikwad https://orcid.org/0000-0001-5487-3294
Krishnamoorthy A https://orcid.org/0000-0002-6840-2677
Vijaykumar S Jatti https://orcid.org/0000-0001-7949-2551
Nitin Ambhore https://orcid.org/0000-0001-8468-8057
Ankit D Oza https://orcid.org/0000-0001-8104-1266
Manoj Kumar https://orcid.org/0000-0003-2815-8443
Manish Gupta https://orcid.org/0000-0002-5232-378X
Unnati A. Joshi https://orcid.org/0000-0003-0018-0913

REFERENCES

1. Ming, W. *et al*. Progress in modeling of electrical discharge machining process. *Int. J. Heat Mass Transf.* **187**, 122563 (2022). https://doi.org/10.1016/j.ijheatmasstransfer.2022.122563
2. Shastri, R.K. *et al*. Reviewing performance measures of the die-sinking electrical discharge machining process: Challenges and future scopes. *Nanomaterials* **12**, 384 (2022). https://doi.org/10.3390/nano12030384
3. Boopathi, S. An extensive review on sustainable developments of dry and near-dry electrical discharge machining processes. *J. Manuf. Sci. Eng.* **144**, 050801 (2022). https://doi.org/10.1115/1.4052527
4. Baroi, B.K. & Patowari, P.K. A review on sustainability, health, and safety issues of electrical discharge machining. *J. Braz. Soc. Mech. Sci. Eng.* **44**, 1–38 (2022). https://doi.org/10.1007/s40430-021-03351-4
5. Kannan, E., Trabelsi, Y., Boopathi, S. & Alagesan, S. Influences of cryogenically treated work material on near-dry wire-cut electrical discharge machining process. *Surf. Topogr.: Metrol. Prop.* **10**, 015027 (2022). https://iopscience.iop.org/article/10.1088/2051-672X/ac53e1
6. Rathod, R., Kamble, D. & Ambhore, N. Performance evaluation of electric discharge machining of titanium alloy — a review. *J. Eng. Appl. Sci.* **69**, 1–19 (2022). https://doi.org/10.1186/s44147-022-00118-z
7. Karthik Pandiyan, G., Prabaharan, T., Jafrey Daniel James, D. & Sivalingam, V. Machinability analysis and optimization of electrical discharge machining in AA6061-T6/15wt.% SiC composite by the multi-criteria decision-making approach. *J. Mater. Eng. Perfor.* **31**, 3741–3752 (2022). https://doi.org/10.1007/s11665-021-06511-8
8. Vora, J. *et al*. Machining parameter optimization and experimental investigations of nano-graphene mixed electrical discharge machining of nitinol shape memory alloy. *J. Mater. Res. Technol*. **19**, 653–668 (2022). https://doi.org/10.1016/j.jmrt.2022.05.076
9. Akıncıog˘lu, S. Taguchi optimization of multiple performance characteristics in the electrical discharge machining of the TiGr2. *F U Mech. Eng.* **20**, 237–253 (2022). https://doi.org/10.22190/FUME201230028A
10. Danish, M. *et al*. M.B. Optimization of hydroxyapatite powder mixed electric discharge machining process to improve modified surface features of 316L stainless steel. *PI Mech. Eng. E-J. Pro.* (2022). https://doi.org/10.1177/09544089221111584
11. Kam, M., I.pekçi, A. & Argun, K. Experimental investigation and optimization of machining parameters of deep cryogenically treated and tempered steels in electrical discharge machining process. *PI Mech. Eng. E-J. Pro.* (2022). https://doi.org/10.1177/09544089221078133
12. Gautam, N., Goyal, A., Sharma, S.S., Oza, A.D. & Kumar, R. Study of various optimization techniques for electric discharge machining and electrochemical machining processes. *Mater. Today: Proc.* **57**, 615–621 (2022). https://doi.org/10.1016/j.matpr.2022.02.005
13. Naresh, C., Bose, P.S.C. & Rao, C.S.P. Shape memory alloys: A state of art review. *IOP Conf. Ser. Mater. Sci. Eng.* **149**, (2016). https://doi.org/10.1088/1757-899X/149/1/012054
14. Soni, H. & Mashinni, P.M. Wire electro spark machining and characterization studies on Ti50Ni49Co1, Ti50Ni45Co5 and Ti50Ni40Co10 alloys. *Mater. Res. Exp.* **7**, (2020). https://doi.org/10.1088/2053-1591/ab6196
15. Chen, Z., Zhang, Y., Zhang, G., Huang, Y. & Liu, C. Theoretical and experimental study of magnetic-assisted finish cutting ferromagnetic material in WEDM. *Int. J. Mach. Tools Manuf.* **123**, 36–47 (2017). https://doi.org/10.1016/j.ijmachtools.2017.07.009
16. Rattan, N. & Mulik, R.S. Experimental investigations and multi-response optimization of silicon dioxide (Quartz) machining in magnetic field assisted TW-ECSM process. *Silicon* **9**, 663–673 (2017). https://doi.org/10.1007/s12633-016-9521-x
17. Manjaiah, M., Narendranath, S. & Basavarajappa, S. A review on machining of titanium based alloys, 2014. *Rev. Adv. Mater. Sci.* **36**, 89–111 (2014).
18. Ozerkan, H.B. Effect of electrode polarity on fatigue life in EDM. *MATEC Web Conf.* **224**, 01107 (2018). https://doi.org/10.1051/matecconf/201822401107
19. Kuo, C.-G., Hsu, C.-Y., Chen, J.-H. & Lee, P.-W. Discharge current effect on machining characteristics and mechanical properties of aluminum alloy 6061 workpiece produced by electric discharging machining process. *Adv. Mech. Eng.* **9**, 1–8 (2017). https://doi.org/10.1177/1687814017730756
20. Mehmood, S., Shah, M., Pasha, R.A., Khushnood, S. & Sultan, A. Influence of electric discharge machining on fatigue limit of high strength aluminum alloy under finish machining. *J. Chin. Inst. Eng.* **40**, 118–125 (2017). http://dx.doi.org/10.1080/02533839.2017.1294993
21. Özerkan, H.B. Theoretical determination of the fatigue strength limit of electrical discharge machined (EDM) AISI 8740 steel. *IOP Conf. Mater. Sci. Eng. Ser.* **393**, (2018).
22. Chahardehi, A. & Mehmanparast, A. Fatigue crack growth under remote and local compression—A state-of-the-art review. *Frattura ed Integrità Strutturale* **35**, 41–49 (2016). https://doi.org/10.3221/IGF-ESIS.35.05
23. Gaikwad, M.U., Krishnamoorthy, A. & Jatti, V.S. Investigating the influence of electrical discharge machining process parameter on fatigue strength during machining of titanium grade-2. *Mater. Today Proc.* **46**, 8951–8957 (2021). https://doi.org/10.1016/j.matpr.2021.05.367
24. Matanda, B.K. *et al*. A review on parametric optimization of EDM process for nanocomposites machining: Experimental and modelling approach. *Int. J. Interact. Des. Manuf. (IJIDeM)* 1–10 (2023). https://doi.org/10.1007/s12008-023-01353-1
25. Y. Darji, *et al*. Experimentation with the EDM parameter through a full factorial technique and optimization using regression analysis with carbon nanotubes. *Int. J. Interact. Des. Manuf. (IJIDeM)* 1–14 (2023). https://doi.org/10.1007/s12008-023-01263-2
26. Sharma, A.K. *et al*. Experimental analysis of Inconel 625 alloy to enhance the dimensional accuracy with vibration assisted micro-EDM. *Int. J. Interact. Des. Manuf. (IJIDeM)* 1–15 (2023). https://doi.org/10.1007/s12008-023-01228-5
27. Surani, K. *et al*. Performance comparison of powder mixed EDM and traditional EDM on TZM-molybdenum super alloy using response surface methodology. *Int. J. Interact. Des. Manuf. (IJIDeM)* 1–12 (2022). https://doi.org/10.1007/s12008-022-01088-5
28. Oza, A.D., Goyal, A., Buch, V. & Kumar, M. Electrochemical discharge machining process: A review on process parameters and future scope. *Mater. Today: Proc.* **62**, 6956–6961 (2022). https://doi.org/10.1016/j.matpr.2021.12.341
29. Kumar, M., Oza, A.D., Prajapati, M. & Joshi, G. Experimental investigation during machining of P20 tool steel using EDM. In *International Conference on Advances in Materials Processing & Manufacturing Applications* (pp. 539–547). Singapore: Springer Singapore, 2020. https://link.springer.com/chapter/10.1007/978-981-16-0909-1_56

© World Scientific Publishing Co.

Innov. Emerg. Technol. 2023.10. Downloaded from www.worldscientific.com
by Joy Quek on 12/17/23. Re-use and distribution is strictly not permitted, except for Open Access articles.

30. Gyurova, L.A. & Friedrich, K. Artificial neural networks for predicting sliding friction and wear properties of polyphenylene sulfide composites. *Tribol. Int.* **44**, 603–609 (2011).
31. Joshi, S.N. & Pande, S.S. Intelligent process modeling and optimization of die-sinking electric discharge machining. *Appl. Soft Comput.* **11**, 2743–2755 (2011).
32. Sathyabalan, P., Selladurai, V. & Sakthivel, P. ANN based prediction of effect of reinforcements on abrasive wear loss and hardness in a hybrid MMC. *Am. J. Eng. Appl. Sci.* **2**, (2009).
33. Liu, G., Huang, C., Zhao, B., Wang, W. & Sun, S. Effect of machined surface integrity on fatigue performance of metal workpiece: A review. *Chin. J. Mech. Eng.* **34**, 118 (2021). https://doi.org/10.1186/s10033-021-00631-x
34. Gaikwad, M.U., Krishnamoorthy, A. & Jatti, V.S. Estimation of surface integrity parameters in Electrical Discharge Machining (EDM) process — A review. In *Techno-Societal 2018* (pp. 601–6014). Springer Nature, 2018. https://doi.org/10.1007/978-3-030-16962-6_61
35. Gaikwad, M.U., Krishnamoorthy, A. & Jatti, V.S. Investigation and optimization of process parameters in Electrical Discharge Machining (EDM) process for NiTi 60. *Mater. Res. Exp.* **6**, 065707 (2019).
36. Gaikwad, M.U., Krishnamoorthy, A. & Jatti, V.S. Investigation on effect of process parameter on surface integrity during electrical discharge machining of NiTi 60. *Multidiscip. Model. Mater. Struct.* **16**, 1385–1394 (2020).
37. Gaikwad, M.U., Krishnamoorthy, A. & Jatti, V.S. Process parameters optimization using Jaya algorithm during EDM machining of Niti60 alloy. *Int. J. Sci. Technol. Res.* **8**, 1168–1174 (2019).
38. Gaikwad, M.U., Krishnamoorthy, A. & Jatti, V.S. Implementation of Jaya algorithm for process parameter optimization during EDM processing of NiTi 60alloy. *Mater. Today: Proceed.* **47**, 5701–5708 (2021).
39. Gaikwad, M.U., Krishnamoorthy, A. & Jatti, V.S. Semi-empirical modeling and jaya optimization of white layer thickness during electrical discharge machining of NiTi alloy. In *Metaheuristic Algorithms in Industry 4.0* (pp. 127–138). CRC Press, 2021.
40. Chaubey, S.K. & Jain, N.K. Investigations on surface quality of WEDM-manufactured meso bevel and helical gears. *Mater. Manuf. Process.* **33**, 1567–1577 (2018). https://doi.org/10.1080/10426914.2017.1415440
41. Liu, J.F. & Guo, Y.B. Residual stress modeling in Electric Discharge Machining (EDM) by incorporating massive random discharges. *Procedia CIRP* **42**, 697–702 (2016). https://doi.org/10.1016/j.procir.2016.02.060
42. Lee, H.T. & Tai, T.Y. Relationship between EDM parameters and surface crack formation. *J. Mater. Process. Technol.* **142**, 676–683 (2003). https://doi.org/10.1016/S0924-0136(03)00688-5
43. Roy, B.K. & Mandal, A. Surface integrity analysis of Nitinol-60 shape memory alloy in WEDM. *Mater. Manuf. Process.* **34**, 1091–1102 (2019). https://doi.org/10.1080/10426914.2019.1628256
44. Mohanty, S., Das, A.K. & Dixit, A.R. Surface integrity and residual stress analysis of μEDM coated Ti-alloy miniature components. *Mater. Manuf. Process.* **36**, 48–58 (2021). https://doi.org/10.1080/10426914.2020.1813894
45. Liu, J.F., Li, C., Fang, X.Y., Jordon, J.B. and Guo, Y.B. Effect of wire-EDM on fatigue of nitinol shape memory alloy. *Mater. Manuf. Process.* **33**, 1809–1814 (2018). https://doi.org/10.1080/10426914.2018.1512125
46. Fu, C.H., Liu, J.F., Guo, Y.B. & Zhao, Q.Z. A comparative study on white layer properties by laser cutting vs. electrical discharge machining of nitinol shape memory alloy. *Procedia CIRP* **42**, 246–251 (2016). https://doi.org/10.1016/j.procir.2016.02.280
47. Kumar, A. *et al*. Comparison in the performance of EDM and NPMEDM using Al_2O_3 nanopowder as an impurity in DI water dielectric. *Int. J. Adv. Manuf. Technol.* **100**, 1327–1339 (2019). https://doi.org/10.1007/s00170-018-3126-z
48. da Fonte, M., Reis, L. & de Freitas, M. The effect of steady torsion on fatigue crack growth under rotating bending loading on aluminium alloy 7075-T6. *Frat. ed Integrità Strutt.* **30**, 360–368 (2014). https://doi.org/10.3221/IGF-ESIS.30.43360
49. Chena, Z., Moverarea, J., Penga, R.L. & Johansson, S. Surface integrity and fatigue performance of inconel 718 in wire electrical discharge machining. *Procedia CIRP* **45**, 307–310 (2016).
50. Pramanika, A. & Basak, A.K. Effect of wire Electric Discharge Machining (EDM) parameters on fatigue life of Ti-6Al-4V alloy. *Int. J. Fatigue* **128**, 10518 (2019).
51. Ghanem, F., Ben Fredj, N., Sidhom, H. & Braham, C. Effects of finishing processes on the fatigue life improvements of electro-machined surfaces of tool steel. *Int. J. Adv. Manuf. Technol.* **52**, 583–595 (2011). https://doi.org/10.1007/s00170-010-2751-y
52. Songsong, L., Rui, B., Ting, Z. & Binjun, F. Mechanism of crack branching in the fatigue crack growth path of 2324-T39 aluminium alloy. *Frat. ed Integrità Strutt.* **35**, 74–81 (2016). https://doi.org/10.3221/IGF-ESIS.35.09
53. Gaikwad, M.U., Ambhore, N. & Bhosale, S.S. Fatigue strength evaluation during EDM machining of titanium alloy. In *Techno-Societal 2016, International Conference on Advanced Technologies for Societal Applications* (pp. 647–653). Cham: Springer International Publishing, 2022. https://doi.org/10.1007/978-3-031-34644-6_66
54. Zhu, J., Shi, Y., Feng, X., Wang, H. and Lu, X. Prediction on tribological properties of carbon fiber and TiO_2 synergistic reinforced polytetrafluoroethylene composites with artificial neural networks. *Mater. Des.* **30**, 1042–1049 (2009). https://doi.org/10.1016/j.matdes.2008.06.045
55. Sreebalaji, V.S. & Kumar, K.R. Artificial neural networks and multi response optimisation on EDM of aluminium (A380)/fly ash composites. *Int. J. Comput. Mater. Sci. Surf. Eng.* **6**, 244–262 (2016). https://doi.org/10.1504/IJCMSSE.2016.081690

© World Scientific Publishing Co.