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Original Article

Analysis of hybrid HA/CNT suspended-EDM process and multiple-objectives optimization to improve machining responses of 316L steel



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ABSTRACT

A low material erosion rate (MER) and a high roughness are challenges encountered when machining the biomaterials using the hydroxyapatite powder (HAp) suspended-electric discharge machining (EDM) process. Thus, a comprehensive analysis is needed as the required machining outputs are highly dependent on EDM process factors due to its stochastic behavior during the operation. In this context, the research aims at a detailed investigation of the EDM process factors on the machining responses and the feasibility of multiple additives mixed-EDM process needed for processing 316L steel to realize its full potential. To improve MER and reduce both surface roughness (SR) and tool erosion rate (TER), a hybrid of carbon nanotubes (CNT) and HAp supported EDM technique is employed. SEM and EDX analyses have validated the machined surface morphology and migration of the elements. The EDM process parametric optimization has been carried out utilizing Taguchi-based orthogonal design assisting to get the lowest both TER and SR of 0.245 mg/min and 1.85 μm , respectively. The highest MER of 26.47 mg/min as a machinability metric is achieved. Peak current, pulse-on time and HA/CNT quantity are found to be significant determinants in MER, SR and TER using the ANOVA method. The predicted best 21 solution sets using multi-objective spotted hyena optimizer (MOSHO) and following the set objective functions are tabulated. The estimated experimental evaluation errors are lower than 10%, indicating that the predicted solution sets are highly accurate. This research offers a novel approach to process the 316L steel for biomedical applications with enhanced machining performances.

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1. Introduction

316L steel is a surgical-grade steel that is widely utilized in the manufacture of fixation devices such as screws, plates, nails and total hip-joints because of its excellent mechanical strength, biocompatibility and corrosion resistance [1–3]. Because of its high hardness and heat resistance, processing 316L steel with the traditional machining techniques including milling, turning, boring, shaping, lathe and so on, is extremely challenging. The propagation of wear and tear is found on the machined surface due to a direct physical action between the workpiece and cutting tool, which degrades the quality of the machined specimen. Furthermore, the traditional fabrication techniques show a low material cutting rate with a high cutting tool erosion rate (TER) [4], leading to poor machining efficiency and an increase in production cost. The machined surface using these conventional processes attributes a high roughness [5,6]. Electrical discharging machine (EDM) operates with an electro-thermal process, which removes the material from both the specimen and tool-electrode by converting the formed electrical energy into the thermal energy [7]. In this process, a huge temperature ranging from 8000 °C to 12000 °C is generated in the plasma channel. During the operation, a tiny space between the sample and the tool-electrode is maintained which makes it enable to machine the conductive materials attributing ductile, brittleness, hard, and a tiny thickness. Consequently, this process is successfully utilized in numerous factories including the dies and molds, automotive, aerospace and biomedical [8–13]. However, the EDM applications are limited by a number of process restrictions, including low material erosion rate (MER), uneven surface integrity with a high roughness (SR), stochastic behavior during the operation and only capable for the conductive materials [5,9,10,14,15].

The machining responses of EDM process including MER, TER and SR depend significantly on the electrical factors such as current, pulse-on/off duration, polarity and potential voltage as well as characteristics of the employed materials. A high application of output power in the ionization channel results in a high MER, TER and SR [16–18]. Gurpreet et al. [19] studied the influences of EDM process factors on MER, TER and SR while processing 316L steel with a copper electrode using a typical EDM technique. Peak current was the most significant factor which affected MER, TER and SR. SEM analysis confirmed presence of the morphological features including cracks and craters on the machined surface. Sudhir et al. [20] investigated how to optimize EDM process factors including peak current, pulse-on time and gap voltage while fabricating AISI 420 steel with a copper electrode. However, the micro-cracks, deep craters and thermal stresses are found on the fabricated surface due to a huge heat energy generation. In addition to this, due to a large temperature formation during the typical EDM process, the electrical resistance of the specimen and tool-electrode rises, bringing them close together to produce the plasma channel. A poor flushing and abnormal electrical sparks occur, resulting in an unstable machining and high SR [5,14,18]. The particle mixed EDM (PM-EDM) process was developed to overcome the limitations of

the traditional EDM method. In this system, the powder material having a high electrical conductivity are added in the fluid medium to enhances the machining responses. Due to repeated electrical sparks production, scouring processes and improved debris flushing, literature shows that adding electrically and thermally conductive additives not only enhances MER, but also reduces SR and TER [14,17,21,22].

Previous research has shown that using hydroxyapatite powder (HAp) in the EDM process results in lower MER and higher SR and TER than using other electrically conductive additives when cutting metallic biomaterials. This occurs because the HAp attributes a low both thermal and electrical conductivity [23–26]. When the 316L steel was machined utilizing the HAp added-EDM process, Lamichhane et al. [24] produced a MER of 19.01 mg/min at a high current density of 28 A and discharge period of 60 μ s. In the study, the current, pulse-on time and HA powder addition were found to be major factors impacting SR, TER and MER. The effects of PM-EDM process factors including peak current, discharge period, HA quantity and duty cycle on thin recast layer (RLT) and SR when fabricating the 316L steel were fully explored in the study by Al-Amin et al. [23]. Peak current influenced both RLT and SR the most, pursued by pulse-on duration and HA quantity. With a current density of 5 A, discharge period (pulse-on duration) of 8 μ s, HA quantity of 10 g/l, a low SR of 2.149 μ m and RLT of 6.22 μ m were obtained. In this study, While processing Ti–Ta alloy employing a HAp added-EDM process with hydrothermal treatment, Ou and Wang [26] investigated the machining responses in terms of MER, SR, and RLT. At a HA quantity of 10 g/l and a current density of 3 A, SR of 2 μ m and RLT of 7 μ m were discovered.

Design of Experiment (DOE) is a strong tool for planning, modelling, and evaluating the impact of various input parameters on outputs. It is a statistical method for developing mathematical models that anticipate possible outcomes depending on the input data or parameters. Box–Behnken design, central composite design (CCD), fractional factorial design (FFD), block design, quasi experimental design, Taguchi method and response surface methodology (RSM), which are known as statistical methods are frequently used in various engineering applications [23,27–30]. These techniques are equally employed in the energy applications [31]. Furthermore, several techniques such as D-optimal design, multivariate chemometric approach, RSM with both FFD and central composite face centered design (CCFCD) and multi-criteria embedded optimization method have been successfully utilized in the solar cells and sensors applications [32–38]. RSM method is typically employed in experimental modeling even though it has significant drawbacks including the inability to solve nonlinear problems, the difficulty in performing with a huge data sets and offering a large number of experiment [39,40]. Taguchi technique is widely accepted DOE offering high quality products with a low cost due to conducting comparatively lower number of experiments than other techniques to achieve the desired outputs. CCD technique provides robust experimental design, which does not show sensitivity to the missing data sets. However, it offers a large number of experiments like RSM [27,41].

The key objective of this study is to improve overall machining responses by increasing MER and decreasing TER and SR while fabricating 316L steel using an EDM technique with the combined carbon nanotubes (CNT) and HAp. Another goal of this research is to look into the effects of adding CNT to HAp and EDM process factors on machining responses. The last aim is to find the best-fitting solutions for the responses by estimating optimal combinations of process variables. Because CNT have a high electrical and thermal conductivity [6], it is hypothesized that adding them to the HAp mixed EDM-oil improves machining responses, which is contrary to sustainability goals. It is expected that the added CNT with HAp mixed-EDM process will reduce the electrical resistivity of HAp mixed EDM-oil causing enlargement of the machining gap, multiple electrical sparks and scouring action. These actions taken by adding the CNT in HAp mixed EDM-oil will improve MER with a decline in TER and SR. The overall system efficiency and metrics of machining responses, nonetheless, are heavily dependent on the EDM process factors due to their stochastic nature during the operation, leading to the necessity of process optimization to obtain the desired responses. For single objective function studies, the Taguchi, response surface methodology (RSM), and grey relational analysis (GRA) are used; however, due to the contradictory nature of the results, they are not used for multiple objective function studies [42–44]. As a result, for the first time, this research applied a novel technique called the multi-objective spotted hyena optimizer (MOSHO) to anticipate the best sets of EDM process parameters for the desired sets of solution. This research provides manufacturers with an innovative and practical procedure for manufacturing the 316L steel with the optimal results. For the first time, this study offers the optimization of hybrid HA/CNT mixed-EDM process variables using the MOSHO technique for processing 316L steel in the industries.

2. Experimental procedures

This section focuses on details of the employed materials, machining technique, design of experiments, preparation of the purchased and machined samples and multi-objective

optimization tool. Overall, this study utilized multiple additives mixed-EDM technique to machine the 316L steel. In total nine experiments were carried out following Taguchi-based L9 design in this study. The machined 316L steel specimens were characterized to measure SR. To quantify the repeatability of results, a test was carried out three times for a specimen which was machined at the same machining conditions and the standard deviation (STDEV) has been calculated. The influence of process parameters on the acquired MER, TER and SR were then investigated using statistical analysis. Finally, the multiple-objective spotted hyena optimizer (MOSHO) technique was applied to obtain the desired sets of solution for the machining responses. The LINMAP (linear programming technique for multidimensional analysis of preference) was also used to get the best solution set.

2.1. Manufacturing process and materials

2.1.1. Experimental method

To machine the 316L steel, a CNC-diesinker-EDM (model: FP60EA; brand: Mitsubishi; country of origin: Japan) was adopted. As a dielectric medium, EDM-oil with an electrical strength of 45 kV A was used. A newly designed tank with a tankage capacity of 20 L was used to maintain a steady flow of HAp and CNT mixed EDM-oil to the operation container with a storage capacity of 200 L. The separated tank consisted of two pneumatic pumps (inlet and outlet) and a pneumatic stir. The pneumatic stir rotates to mix the employed additives in the EDM-oil. Figure 1 shows a schematic depiction of the used PM-EDM process. A machining depth of 0.7 mm was employed throughout the studies, with a 0.01 mm operation gap between the workpiece and the tool-electrode. The electrical variables used in the studies were peak current, pulse-on time and duty cycle. Table 1 provides information regarding the machining conditions of PM-EDM process to conduct all of the experiments.

2.1.2. Materials

To prepare the workpieces, a surgical grade 316L austenitic stainless-steel plate measuring $5 \times 400 \times 400$ mm was obtained from Mechatech Solution in Malaysia and cut into

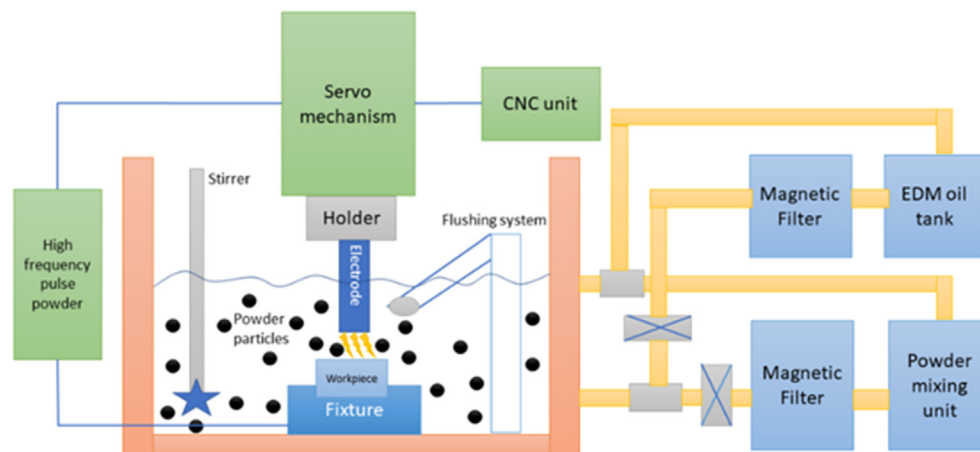


Fig. 1 – A schematic model of used PM-EDM technique [reproduced with permission from ref. [1]].

Table 1 – Machining conditions for PM-EDM process.

Factors	Unit	Levels
Peak current	A	5; 7; 10
Pulse-on time	μs	8; 12; 16
HA amount	g/l	7; 10; 15
Duty cycle	%	45; 50; 55
CNT amount	g/l	0.5
Polarity	(+ or -)	(+)
Gap voltage	V	150
Cutting depth	mm	0.7

pieces (dimension: $5 \times 9 \times 10$ mm) employing the wire cut-EDM. Surface morphology and elemental compositions of the prepared 316L steel utilizing SEM and EDX spectrums, respectively, are depicted in Fig. 2a, b. The surface of the purchased 316L steel is smooth and defect-free, as shown in Fig. 2a. The elemental spectrum confirms the presence of Fe, Cr, Ni and Mo, resulting in excellent agreement with 316L steel demonstrated in Fig. 2b. A commercial titanium purchased from the Mechatech Solution, Malaysia, was adopted as tool-electrode material because of having biocompatibility and low wear rate [23]. The purchased titanium was sliced into pieces of $85 \times 9.5 \times 10.5$ mm using the Wire cut-EDM. Faces of the prepared titanium electrode were milled by the milling machine and polished by the polisher machine (model of

polisher machine: Metaserv_250) to make them smooth. HAP having an average particle size of 40 nm and CNT with a purity of 95% were purchased from Mechatech Solution in Malaysia and were used as the additives. Figure 3a, b shows the microstructure and elemental composition of as received CNT. The content of C is 94.9 wt% while the rest content is for few impurities such as Ni, Al, Co and Fe as demonstrated in Fig. 3b. The purity of CNT was determined by thermogravimetric analysis (TGA) at temperatures ranging from 25 to 900 °C with a temperature increment of 10 °C per minute. The obtained CNT was found to be 91.35% pure according to TGA analysis shown in Fig. 4. Table 2 provides information on physical properties of the used materials.

2.2. Experimental model employing Taguchi's method

Taguchi uses a rigorous experimental design (DOE) offering the minimal number of potential runs to obtain the best results due to cost and time restrictions. It offers an orthogonal array to establish the DOE and the signal/noise ratio (S/N) is used to determine the appropriate settings for the controlled variables to produce the desired results [6,42]. Using the Minitab 19 Pro software, a Taguchi-based L9 model was built to conduct the experiments. The process factors such as peak current, pulse-on time, HA/CNT amount and duty cycle have been elected after thorough literature review and enough trail

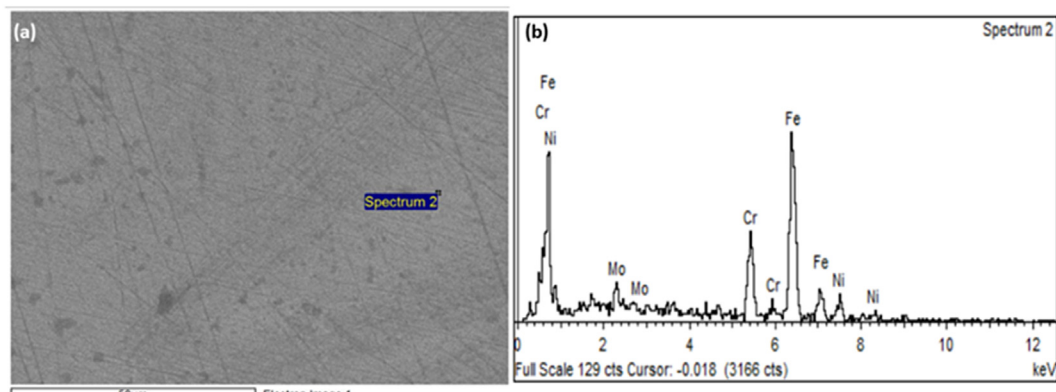


Fig. 2 – Characterizations of as received 316L steel: (a) SEM image and (b) EDX spectrum.

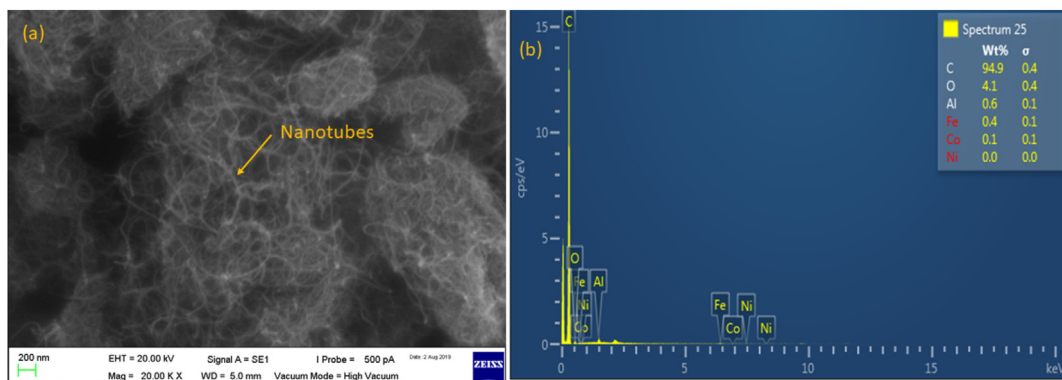


Fig. 3 – Characterizations of as received CNT: (a) SEM image and (b) EDX spectrum.

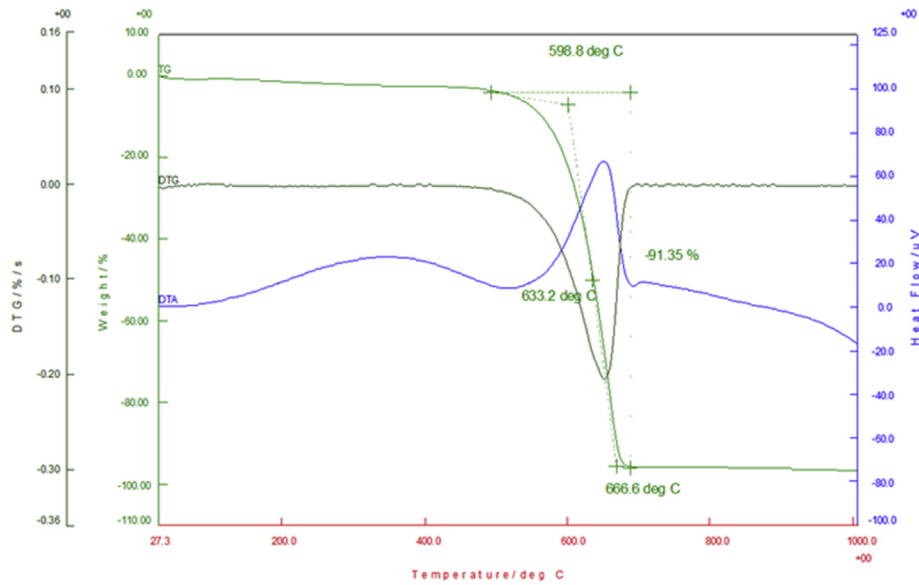


Fig. 4 – TGA report showing purity of CNT.

Table 2 – Physical characteristics of used materials [12].

Materials	Density (g/cm ³)	Thermal conductivity (W/mK)	Melting point (°C)	Electrical resistivity (μohm.cm)
316L steel	7.9	17	1648	81
Titanium	4.72	22	1940	55
Hydroxyapatite	3.08	0.01	1250	Higher
MWCNT	2	4000	2800	Higher than copper

experiments to examine their effects on the performances including MER, SR and TER. From the experimental point of view, MER was chosen for the maximization, whereas both TER and SR were preferred for the minimization. The Minitab 19 Pro software was used to determine the S/N ratio, which is a loss of quality of function conforming the given mathematical equations (i) and (ii).

Greater-the-better

$$S/N = -10 \log \left[1/n \sum_{i=1}^n 1/y^2 \right] \quad (i)$$

Smaller-the-better

$$S/N = -10 \log \left[1/n \sum_{i=1}^n y^2 \right] \quad (ii)$$

where y presents the n th order of MER, SR and TER.

The equation (iii) was used to create first-order mathematical models with non-linearity.

$$Y = \beta_0 + \sum_{i=1}^n \beta_i X_i + \sum_{i < j=2}^n \beta_{ij} X_i X_j + \alpha \quad (iii)$$

where Y is the response, β means the regression coefficient, n denotes the number of independent variables (process factor), X denotes the independent variables, and α defines the error value.

2.3. Machining performances

MER and TER were calculated following the equation (iv):

$$\text{MER or TER} = (W_b - W_a) / \text{machining time} \quad (iv)$$

where W_b means mass of the specimen or tool-electrode before machining and W_a means mass of the work-part or electrode after machining. The machining time was recorded during the experiments. W_b and W_a were measured using a digital weight measuring equipment (model: MettlerToledo ME3002) with a measuring resolution of 0.01g.

A profilometer (brand and model: Mitutoyo and SV3000, respectively; country of origin: Japan) was adopted to calculate the arithmetic surface roughness (SR) obeying the ISO 3274-1996 standard. The maximum tracing distance of the stylus probe was allowed to 7 mm conducting the tests. Each test for a specific sample was carried out for three times and the average was accounted to get SR. As soon the stylus reaches the selected length, the vertical motion of the stylus is converted into an electrical signal by the transducer and analyzed by digital technique. The display shows the profile of peaks with SR value.

The mounting press (model of machine: Simplotmet@1000; country of origin: USA) was used to attach the machined specimens to confirm the alignment, which is badly required during the scanning electron microscope (SEM) and electron dispersive X-ray (EDX) analyses. The prepared specimens were considered to conduct the surface morphological and elemental analyses employing SEM and EDX techniques (brand: Phenom; model: Pro X; origin: Netherlands), respectively. During the analyses, the power supply of 20 kV and magnification of imaging ranging from 500× to 1500X were considered. To conduct the surface morphology through this method, ASTM F1877 standard was followed.

2.4. Multi-objective optimization employing MOSHO

Throughout the last two decades, meta-heuristic optimization algorithms such as the genetic algorithm (GA), particle swarm optimization (PSO), ant colony optimization (ACO), and grey wolf optimizer (GWO) have been utilized to optimize decision variables in a number of industries. Physical phenomena, animal behavior and evolutionary notions all influenced these techniques. The literatures, however, show that due to the tuning of the related variables, these techniques require multiple trials to attain the target [45,46]. To overcome this issue, the spotted hyena optimizer (SHO) proposed by Gaurav and Vijay is inspired by the spotted hyena behavior. This technique was created based on the social link between spotted hyenas and their cooperation behavior and it was utilized to optimize a single objective [47]. Afterwards, MOSHO was developed by integrating three main components, including a) an archive for sorting the non-dominated solutions, b) a group selection approach to know location of the prey from the archive and c) a grid technique to enhance the nondominated targets in the archive [48–50]. MOSHO gave the Pareto's optimal borders of the solution sets in this investigation, which was done with the MATLAB software. Figure 5 shows the flow chart of MOSHO. Table 3 provides information on the parameters setting for

Table 3 – Parameter settings for conducting MOSHO.

Name of parameters	Numerical value
Number of populations	100
Number of iterations	100
Archive size	50
Grid inflation parameter (alpha)	0.1
Leader selection pressure (beta)	4
Extra repository member selection pressure (gamma)	2
H	5 to 0

conducting the MOSHO. Because satisfying several objective functions simultaneously is difficult, different decision-making strategies have been used, including LINMAP, fuzzy non-dimensional and technique for order performance by similarity to ideal solution (TOPSIS) [6,51]. In this study, LINMAP technique was applied finding the most preferable set of solution among the obtained solution sets following the equation (v) [52].

$$E_{di+} = \sum_{j=1}^m (F_{ij} - F_j^{ideal})^2, i = 1; \dots; n \quad (v)$$

where m represents the objective numbers, i means each solution set and F_j^{ideal} indicates the ideal value.

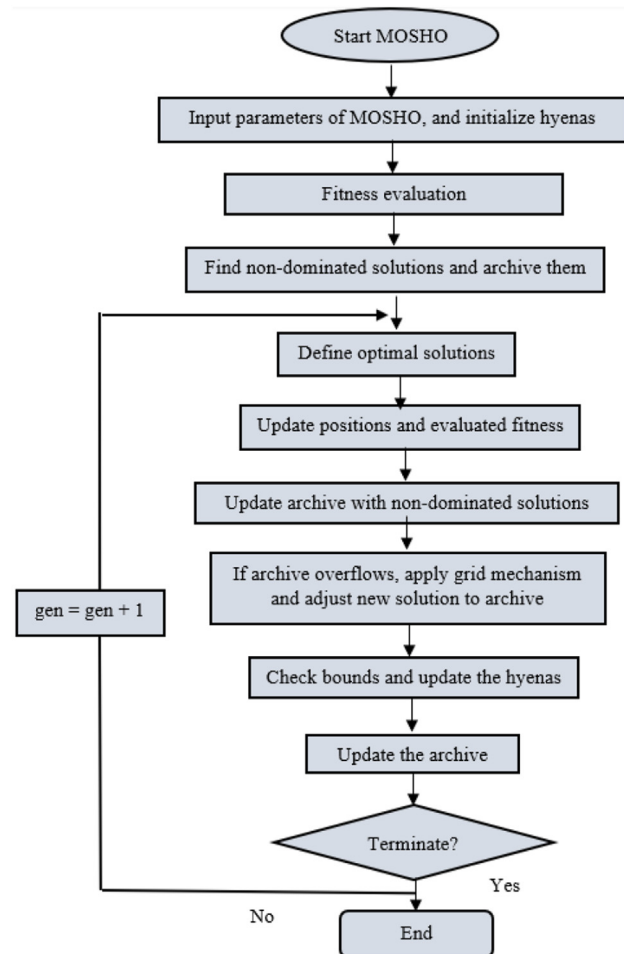


Fig. 5 – Flow chart of spotted hyena optimizer (SHO) [reproduced with permission from ref. [29]].

3. Results and discussion

This section displays the experimental data obtained from Taguchi-based L9 orthogonal array tests. The results that support the study research questions, research framework and methods are highlighted in this section.

3.1. Parametric effects analysis on the responses

3.1.1. Effects of EDM process factors on MER

In Fig. 6a–c, the surface plots of MER are shown by adjusting two process variables while keeping the remaining components constant [6,53]. In Fig. 6a, when the current density (peak current) and discharge period (pulse-on time) are increased, MER increases. However, MER lowers sharply at a 7 A current density and 12 μ s discharge period. The highest MER of 26.47 mg/min was found at a current density of 10 A and discharge period of 16 μ s, while the lowest MER of 2.67 mg/min was measured at a current density of 5 A and discharge period of 8 μ s. From Fig. 6b, with 0.5 g/l CNT, it is demonstrated that increasing both the current density and HA quantity increases MER. The maximum MER is calculated at a current density of 10 A and HA quantity of 15 g/l with 0.5 g/l CNT, whereas the minimum MER is found corresponding to a 5 A current density and 10 g/l HA quantity with 0.5 g/l CNT. In Fig. 6c, an upward trend of MER is noticed for increasing both the discharge period and HA quantity with 0.5 g/l CNT. The highest MER is obtained at a 16 μ s discharge period and 15 g/l HA quantity with 0.5 g/l CNT. However, the smallest MER is found at a HA quantity of 10 g/l with 0.5 g/l CNT and discharge period of 8 μ s. It is concluded that a high discharge energy and HA period with 0.5 g/l CNT is required to obtain a high MER.

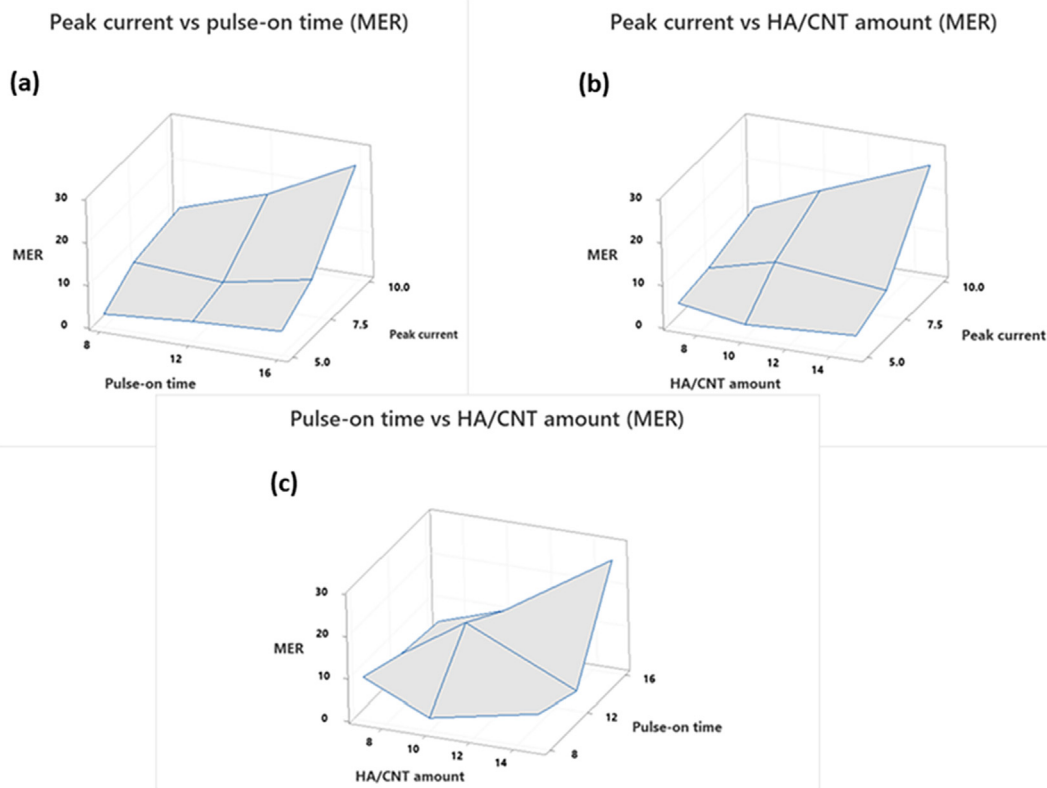


Fig. 6 – 3D surface plots of MER: (a) A vs. B, (b) A vs. C, (c) B vs. C.

From the above analysis in this section, MER increases as the peak current and pulse-on duration are increased, owing to the supply of extraneous electrical sparks that are transformed into thermal energy in the ionization channel, producing more melting and material erosion [5,14,18]. However, at a current density of 7 A and discharge period of 12 μ s, MER drops dramatically due to an unstable machining caused by the short circuiting [23]. Because of the bridging impacts between the electrified particles, increasing the HA amount with a high electrical energy and using the CNT enhances MER. The bridging effects resulted from the capacitive action in the maintained gap, resulting in the formation of multiple electrical sparks in the machining zone [54], which improve MER. Since HA attributes a low electrical conductivity, it reduces the machining gap causing an inferior flushing during the operation and increase the electrical resistivity of the EDM-oil resulting in missing of electrical sparks and unstable machining [23]. Hence, the addition of CNT in the HA-mixed EDM-oil assisted to create a plasma channel within a short duration and the multiple electrical sparks. In addition to this, the added CNT increased the machining gap, which ensured a stable machining condition caused by adequate flushing of the produced debris. Due to adding CNT in the HA mixed-EDM process, this study witnessed a high MER compared to the HA mixed-EDM process conducted by the previous studies [23–26,55].

3.1.2. Impacts of EDM process factors on TER

The surface plots of TER are shown in Fig. 7a–c. In Fig. 7a, overall, TER improves, while ameliorating both the current

intensity (peak current) and discharge period (pulse-on time). TER of 2.64 mg/min being the largest value is obtained at a 10 A current intensity with 16 μ s discharge period, whereas TER of 0.245 mg/min being the lowest value is calculated corresponding to a 5 A current density with 8 μ s discharge period. In Fig. 7b, it is observed that TER rises due to the increment of both the HA/CNT amount and peak current. A lower TER is found at a 7/0.5 g/l HA/CNT amount compared to a 15/0.5 g/l HA/CNT amount though the applied peak current is same. The lowest and maximum TER are found at the intersections of (5 A current density, 10/0.5 g/l HA/CNT quantity) and (10 A current density, 15/0.5 g/l HA/CNT quantity). In Fig. 7c, overall, when both the discharge period and amount of HA rise with 0.5 g/l CNT, an increased trend in TER is seen. When the discharge period is 8 μ s and the HA/CNT quantity is 10/0.5 g/l, the lowest TER is observed, whereas the highest TER is obtained when the discharge period is 16 μ s and the HA/CNT quantity is 15/0.7 g/l. It is concluded that a low discharge energy and a high HA amount with 0.5 g/l CNT are needed to achieve a low TER.

From the above analyses, a high application of the pulse-on time and peak current increases TER because of increasing thermal energy in the ionization channel, which results in a rise of materials erosion from the tool-electrode [14]. In addition to this, TER improves with a high current density and discharge period though the HA quantity of 15 g/l with 0.5 g/l CNT is applied. This occurs because of the multiple electrical sparks formation during the machining [6]. Though a high tool-electrode erosion causes an unstable operation due to the

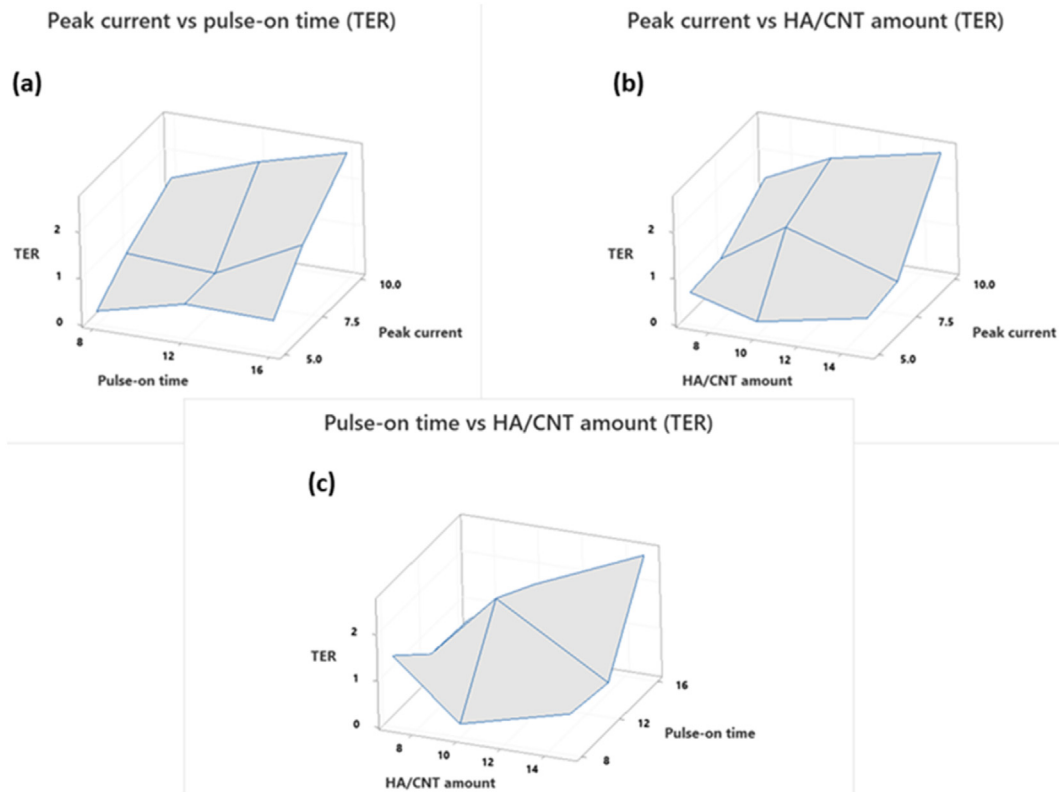


Fig. 7 – 3D surface plots of TER: (a) A vs. B, (b) A vs. C, (c) B vs. C.

uncontrolled machining gap [22], a desired level of tool-electrode erosion is required for the biocompatible coating formation [21,56] due to migration of the eroded debris on the fabricated surface. Addition of CNT particles in the HA mixed-EDM process yields comparatively lower TER than that was obtained using the HA mixed-EDM process [24–26].

3.1.3. Effects of EDM process parameters on SR

From the 3D plots of Fig. 8a, it is shown that SR increases as the current density (peak current) and discharge period (pulse-on time) are increased. SR of 3.38 μm being the largest value is estimated at a 10 A current density with 8 μs discharge period while SR of 1.85 μm being the lowest value is calculated corresponding to a 5 A current density with 8 μs discharge period. A higher SR of 3.38 μm is observed for the combinations of 10 A current density and 8 μs discharge period than that of 3.16 μm obtaining at a current density of 10 A with a discharge period of 16 μs . In Fig. 8b, when the current density increases and the HA quantity drops with 0.5 g/l CNT, SR shows an upward trend. The biggest SR value is discovered at a HA amount of 7 g/l with 0.5 g/l CNT and a current density of 10 A while the least SR value is estimated at a HA quantity of 10 g/l with 0.5 g/l CNT and a current density of 5 A. From Fig. 8c, overall, increasing the pulse-on time and decreasing the HA quantity with 0.5 g/l CNT increases SR. When the discharge period is 16 μs and the HA quantity is 15 g/l with 0.5 g/l CNT, SR is the highest, whereas when the discharge

period is 8 μs and the HA quantity is 10 g/l with 0.5 g/l CNT, it is the lowest. It is concluded that a low discharge energy and a high HA amount with 0.5 g/l CNT are also required to obtain a small SR.

From the above analyses, because of the creation of large craters on the machined surface, using a high pulse-on duration and peak current improves SR [14,18]. Adding the HA powders of 7 g/l and 0.5 g/l CNT in the dielectric oil provides rougher surface compared to applying HA amount of more than 7 g/l with 0.5 g/l CNT. This occurs owing to a high settling propensity of the HAP in the EDM-oil resulted from its high molecular weight [23]. Because of the rapid settling tendency, the added HA particle availability in the machining gap decreases, resulting in a big size and anomalous electrical spark creation, causing a rougher surface. The previous researches studied on the HA mixed-EDM process witnessed a rougher surface compared to this study [23,25,26]. Because HA particles have a low electrical conductivity, the tool-electrode moves close to the specimen for breaking the insulation strength of the EDM-oil resulting in a poor flushing system. Due to inferior flushing of the formed debris, the abnormal sparks and short circuiting are produced, forming the large craters on the machined surface. Furthermore, a few charged debris get stuck on the electrode surface, which form the craters similar to the shape of them on the machined surface [56]. However, addition of the CNT particles in the HA mixed EDM-oil reduces the electrical resistivity of it, causing the

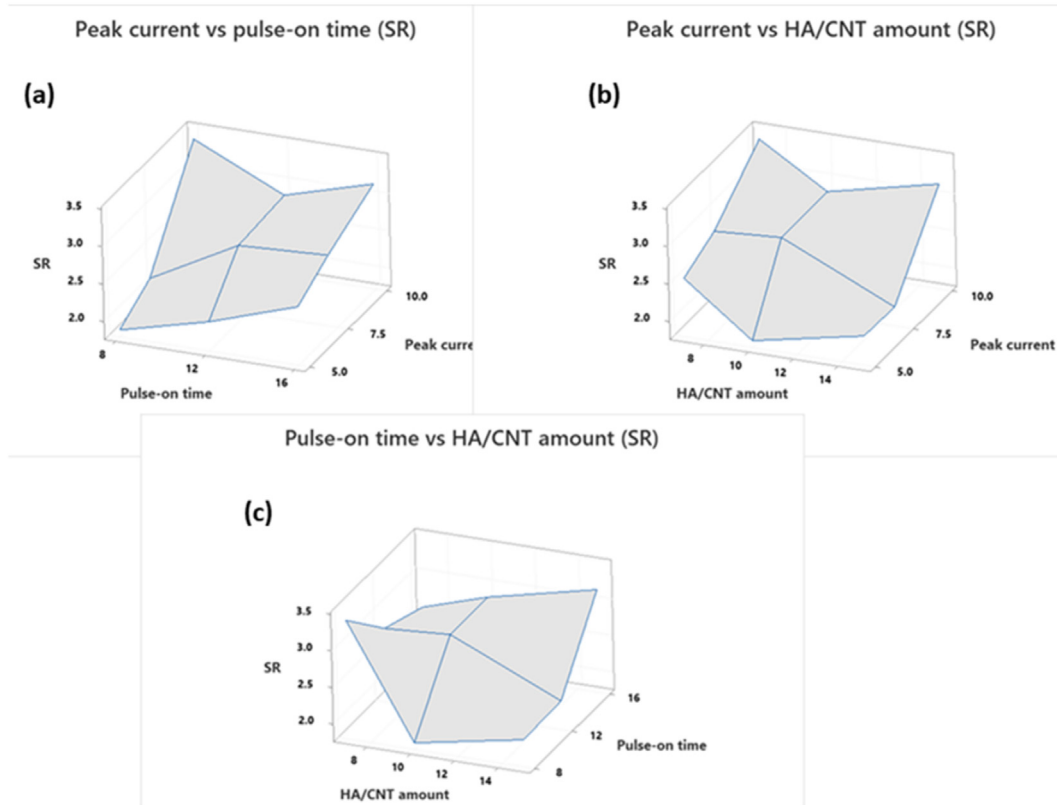


Fig. 8 – 3D surface plots of SR: (a) A vs. B, (b) A vs. C, (c) B vs. C.

enlargement of machining gap. An excellent flushing of the formed debris is occurred due to the increment of gap leading to the stable machining conditions. In addition to this, presence of the added particles in the gap is increased, resulting in the multiple electrical sparks formation due to the chin-like generation among the charged particles [54]. The narrow sized electrical sparks form the shallow craters on the machined surface, causing a low SR. The charges debris occur scouring action on the machined due to the generated electromagnetic forces resulting a low SR as well [14,57]. Figure 9a, b shows the roughness profiles of processed specimens at various parameter values. The smallest SR of $1.85 \mu\text{m}$ was estimated with a current density of 5 A, discharge period of $8 \mu\text{s}$, HA/CNT quantity of $10/0.5 \text{ g/l}$, and duty cycle of 45% as

displayed in Fig. 9a, whereas SR of $3.16 \mu\text{m}$ was obtained with a current density of 10 A, $16 \mu\text{s}$ discharge period, HA/CNT quantity of $15/0.5 \text{ g/l}$ and duty cycle of 45% as presented in Fig. 9b. Table 4 shows quantitatively repeatability of the estimated SR. The table provides that the calculated STDEV is close to zero indicating a high reproducibility of the results.

3.1.4. Parametric effects on surface morphology and elemental compositions

The machined 316L steel surface morphology at different machining conditions is demonstrated in Fig. 10a, b. Overall, the machined surfaces having the morphological and topographical features such as nanopores, micropore, shallow craters, sphere debris and unflushed debris are found. This is

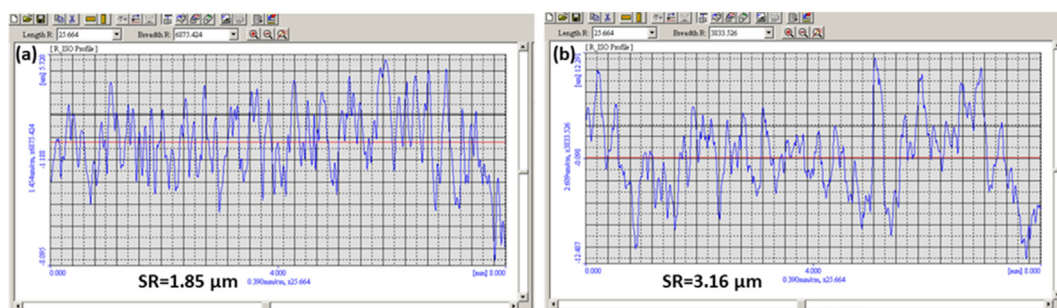


Fig. 9 – The obtained surface roughness profiles at (a) 5 A, $8 \mu\text{s}$, $10/0.5 \text{ g/l}$, 45% and (b) 10 A, $16 \mu\text{s}$, $15/0.5 \text{ g/l}$, 45%.

Table 4 – Quantitatively repeatability of the obtained SR.

Run	Surface roughness (μm)			Mean	STDEV
	SR #1	SR #2	SR #3		
1	1.79	1.81	1.95	1.85	0.087
2	2.15	2.19	2.11	2.15	0.04
3	2.48	2.59	2.55	2.54	0.06
4	2.19	2.13	2.07	2.13	0.06
5	2.84	2.66	2.78	2.76	0.09
6	2.65	2.89	2.92	2.82	0.15
7	3.25	3.3	3.69	3.38	0.24
8	2.76	2.87	2.83	2.82	0.06
9	3.33	3.16	2.99	3.16	0.17

because incorporating CNT powders into the HAP-mixed dielectric fluid reduces the dielectric medium resistive strength, allowing for the expansion of the discharge gap and the creation of a chain-like structure between the electrified powders, resulting in uniform spark dispersion [14,54]. In Fig. 10a, at a low current density of 5 A, discharge period of 12 μs , HA/CNT quantity of 15/0.5 g/l and duty factor of 0.5, the machined specimen shows comparatively shallow craters and lower number of unflushed debris than those found for the machined specimen at 10 A current density, 16 μs discharge period, 15/0.5 g/l HA/CNT quantity and 0.45 duty factor as shown in Fig. 10b. Due to increasing size and number of the craters and unflushed debris, an increase in SR at a high current density and discharge period applications is observed. The machined 316L steel surfaces are free of microcracks at any machining conditions, which occurs due to application of

highly heat conductive CNT powders in the HAP mixed mineral oil. The additional CNT particles absorb a lot of heat from the machined surface during the operation, which reduces thermal stresses in the modified surface and helps with uniform cooling throughout the solidification process [6]. However, the previous studies on HAP added-EDM process showed surface defect, such as cracks, on the fabricated surface [24,58,59]. The elemental composition of the machined 316L steel specimens at different machining conditions are depicted in Fig. 11a, b. At a low discharge energy and HA amount with 0.5 g/l CNT application, the content of Ti on the machined surface is 1.2 wt% as shown in Fig. 11a, while the content improves to 0.5 wt% at a high discharge energy and HA amount with 0.5 g/l CNT application depicted in Fig. 11b. This is because of the insufficient flushing of the debris caused by inadequate enlargement of the operation gap. An improvement of Ca, C and P contents to 13.8 wt%, 25.4 wt% and 7.5 wt%, respectively, is observed at a high discharge energy and HA amount with 0.5 g/l CNT application due to a high quantity of both HA and CNT presence in the operation gap, caused by the sufficient enlargement of the gap.

3.2. Parametric significance analysis

3.2.1. Parametric significance on MER

Table 5 shows the abridged of ANOVA results for MER, SR and TER. The models were evaluated using a 95% confidence level or a 5% significance level ($\alpha = 0.05$) [6,60]. From Table 5, R-sq (adj) and R-sq have values of 91% and 95%, respectively,

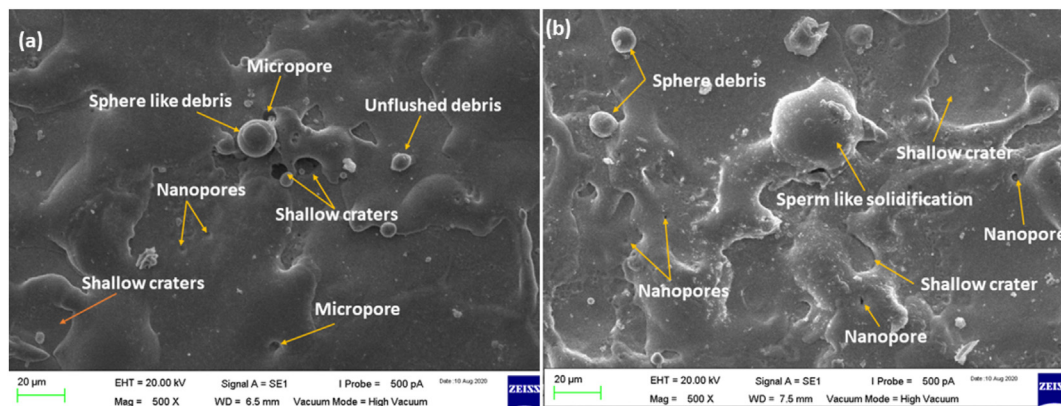


Fig. 10 – Surface morphology of machined 316L steel at (a) 5 A, 12 μs , 15/0.5 g/l, 50% and (b) 10 A, 16 μs , 15/0.5 g/l, 45%.

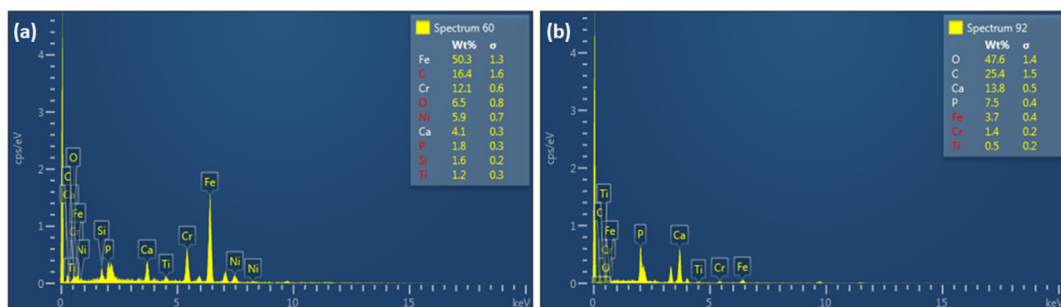


Fig. 11 – Elemental composition of machined 316L steel at (a) 5 A, 12 μs , 15/0.5 g/l, 50% and (b) 10 A, 16 μs , 15/0.5 g/l, 45%.

Table 5 – Summary of ANOVA analyses for MER, TER and SR.

Responses	Factors with p value				Model accuracy		Contribution			
	A	B	C	D	R-sq (%)	R-sq (adj%)	A (%)	B (%)	C (%)	D (%)
MER (mg/min)	0.002	0.02	0.042	0.349	95	91	64.55	17.91	11.11	1.43
TER (mg/min)	0.0001	0.006	0.043	0.938	97.39	94.79	74.23	15.17	7.99	0
SR (μm)	0.004	0.027	0.031	0.345	96.28	92.78	67.43	14.29	12.73	1.83
	MER	TER	SR							
Regression model	0.006	0.002	0.002							

confirming that the regression model provides robust analysis of the process variables for MER. Peak current (0.002), HA/CNT quantity (0.042) and pulse-on time (0.02) have P values lower than 0.05, indicating that they are statistically significant for MER, according to earlier investigations [23,24,61]. However, duty cycle shows a large P value of 0.349 for MER. The contributions of A, B and C are 64.55%, 17.91% and 11.11%, respectively to MER. It is explicit that the addition of CNT in HA-mixed EDM process affected MER significantly.

3.2.2. Parametric significance on TER

ANOVA results of TER is tabulated in Table 5. From Table 5, R-sq (adj) and R-sq have values of 94.79% and 97.39%, respectively, ensuring that the regression design provides an excellent analysis of the process parameters for TER. Peak current (0.0001), pulse-on time (0.006) and HA/CNT quantity (0.043) affect TER significantly, since the P values achieved by them are smaller than 0.05, which follows the previous studies [24,61,62]. Nonetheless, the P value of duty cycle (0.938) is higher than 0.05. The process factors including A, B and C contribute to TER by 74.23%, 15.17% and 7.99%, respectively. Hence, the addition of CNT in HA mixed-EDM process along with the discharge energy influenced TER.

3.2.3. Parametric significance on SR

Table 5 provides information on ANOVA results of SR as well. In Table 5, the R-sq (adj) and R-sq findings are 92.78% and 96.28%, respectively, indicating that the regression design

provides a robust exploration of the process parameters for SR. Peak current (0.004), discharge period (0.027) and HA/CNT quantity (0.031) reveal their significance for SR, as the obtained P values are smaller than 0.05, following the previous studies [6,23,24]. The contributions of process variables such as A, B and C show 67.43%, 14.29%, and 12.73%, respectively, to SR. It is concluded that the addition of CNT in HA mixed-EDM process along with the discharge energy affected SR as well.

3.3. S/N ratio for machining responses

The divergence of a designed parameter from its true value is represented by the quality loss function, which is a continuous function. A large S/N value offers the desired combination of EDM process parameters for a desired machining performance [6,42]. Since a high MER and a low both SR and TER were the desired mode, the larger-the-better was considered for MER. However, the smaller-the-better was selected for both SR and TER. Table 6 provides data on Taguchi-based design with the outputs and S/N ratios. From Table 6, for MER, run #9 has the highest S/N ratio. Hence, a current density of 10 A, duty cycle of 45% (duty factor of 0.45), HA/CNT quantity of 15/0.5 g/l and discharge period of 16 μs was the optimal combination providing the maximum MER. For both SR and TER, run #1 exhibits the highest S/N ratio values. Therefore, the minimization of both SR and TER was obtained at a 5 A current density, 10/0.5 g/l HA/CNT quantity, 8 μs discharge period and 0.45 duty factor. It is concluded that

Table 6 – Taguchi-based L9 design with responses and S/N ratio.

Run	Process factors				Responses					
	A (A)	B (μs)	C (g/l)	D (%)	MER (mg/min)	S/N ratio for MER	T-ER (mg/min)	S/N ratio for TER	SR (Ra) (μm)	S/N for SR
1	5	8	10/0.5	45	2.67	8.5302	0.245	12.2167	1.85	−5.3434
2	5	12	15/0.5	50	4.22	12.5062	0.701	3.0856	2.15	−6.6488
3	5	16	7/0.5	55	5.21	14.3368	0.652	3.715	2.54	−8.0967
4	7	8	15/0.5	55	7.76	17.7972	0.84	1.5144	2.13	−6.5676
5	7	12	7/0.5	45	6.33	16.0281	0.713	2.9382	2.76	−8.8182
6	7	16	10/0.5	50	10.28	20.2399	1.63	−4.2438	2.82	−9.005
7	10	8	7/0.5	50	9.78	19.8068	1.49	−3.4637	3.38	−10.578
8	10	12	10/0.5	55	16.35	24.2704	2.143	−6.6204	2.82	−9.005
9	10	16	15/0.5	45	26.47	28.4551	2.64	−8.4321	3.16	−9.9937
Factors	Symbols									
Peak current	A									
Pulse-on time	B									
HA/CNT amount	C									
Duty cycle	D									

run #9 is preferred for the largest MER, but run #1 is chosen for the lowest both TER and SR.

3.4. Main effect analyses and mathematical model construction for responses

Current density (peak current), HA/CNT quantity and discharge period (pulse-on time) are clearly influential factors for MER, SR and TER, as demonstrated in the main effect plots of the responses in Fig. 12a–c. Current density, discharge period and HA/CNT quantity are the most important factors for all responses, while HA/CNT quantity shows an unusual trend for SR only. From Fig. 12a, the maximum MER is anticipated at a current density of 10 A, discharge period of 16 μ s, HA/CNT quantity of 15/0.5 g/l, and duty cycle of 55%. In Fig. 12b, the minimal TER for a 5 A current density, 7/0.5 g/l HA/CNT quantity, 8 μ s discharge period, and 45% duty cycle is calculated. The optimal process factors of 5 A current density, 8 μ s discharge period, 15/0.5 g/l HA/CNT quantity and 55% duty cycle provide the lowest SR as shown in Fig. 12c. It is concluded that a large use of discharge energy and HA/CNT quantity deserves a high MER, while a low application of them is preferable for the lowest TER. In addition to this, the smallest SR is obtained while applying a low discharge energy with a high HA/CNT amount.

The plots of normal probability of the responses are demonstrated in Fig. 13a–c. The figures show that a few residuals take position on the standard lines, indicating the chosen process variables importance and the errors being normally allotted [53].

Finally, ordinary form of the regression-based mathematical models for MER, SR, and TER were constructed using the raw data taken from Table 6, which are given as follows:

$$\text{MER} = 17.90 - 2.164*A - 1.857*B - 3.313*C + 0.2425*D \\ + 0.1136*A*B + 0.2878*A*C - 0.1472*B*C$$

$$\text{TER} = -0.92 + 0.010*A - 0.274*B - 0.115*C + 0.0534*D \\ + 0.0288*A*B - 0.0086*A*C + 0.0161*B*C$$

$$\text{SR} = -0.488 + 0.7004*A + 0.4011*B - 0.0368*C - 0.0533*D \\ - 0.04903*A*B + 0.00715*A*C - 0.00020*B*C$$

where A is the peak current, B is the pulse-on time, C is the HA/CNT amount and D is the duty cycle.

To ensure that the responses are predictable, regression equations are first constructed. These equations are then used to build MOSHO, which allows the models to be further optimized. The criteria of the multi-objective optimization are to discover the minimum values of both SR and TER and the maximum values of MER. The optimization is difficult due to the contradicting nature of responses. Therefore, Taguchi-integrated MOSHO is used for better prediction and optimization.

3.5. Optimization of the EDM process variables for responses

When MER improves, machining performances such as TER and SR improve, according to experiments. Furthermore,

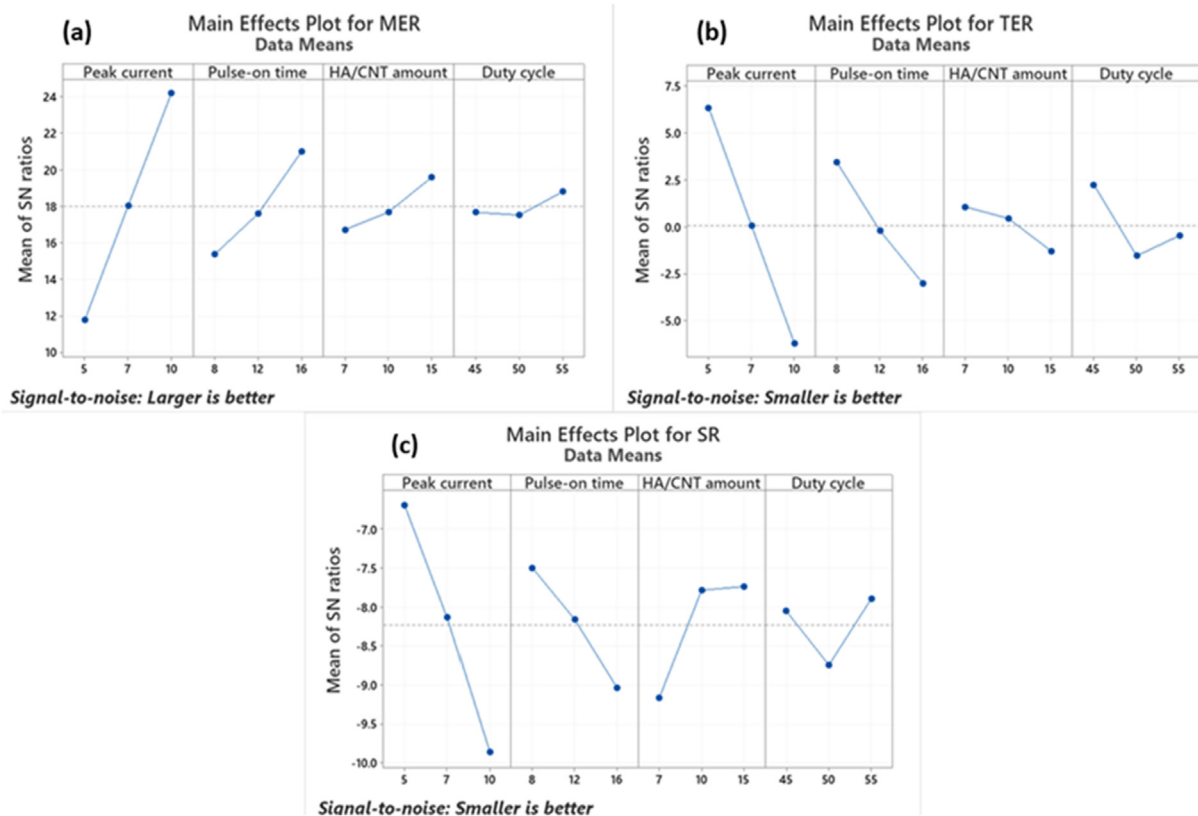


Fig. 12 – Main effect plots for (a) MER, (b) TER, c) SR.

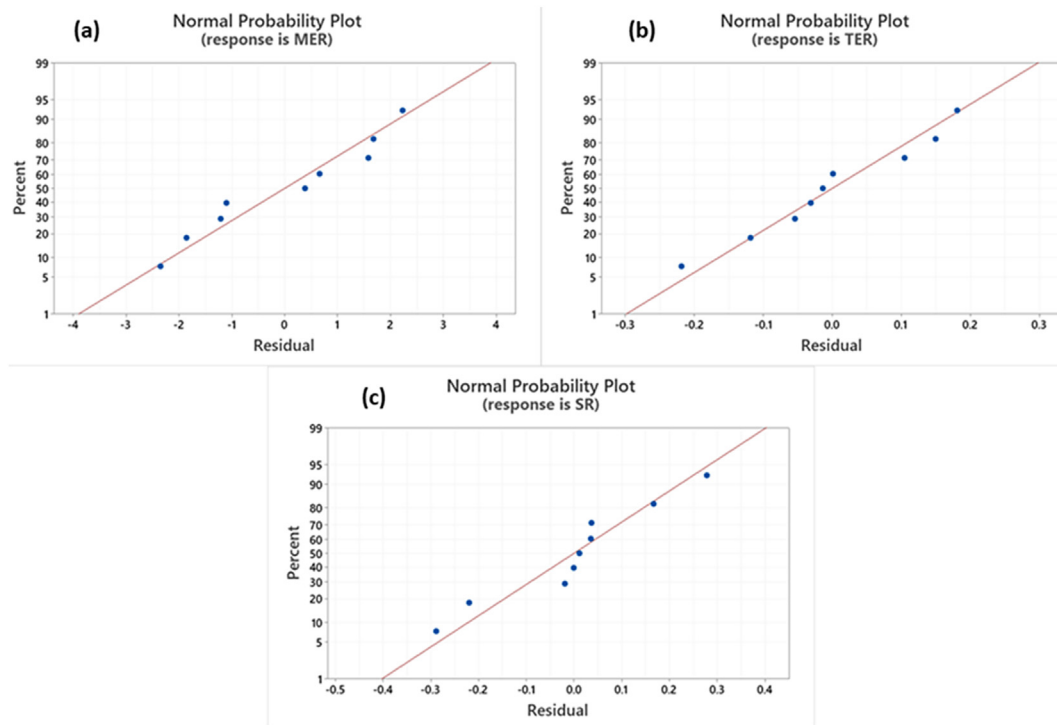


Fig. 13 – Normal probability plots for (a) MER, (b) TER, (c) SR.

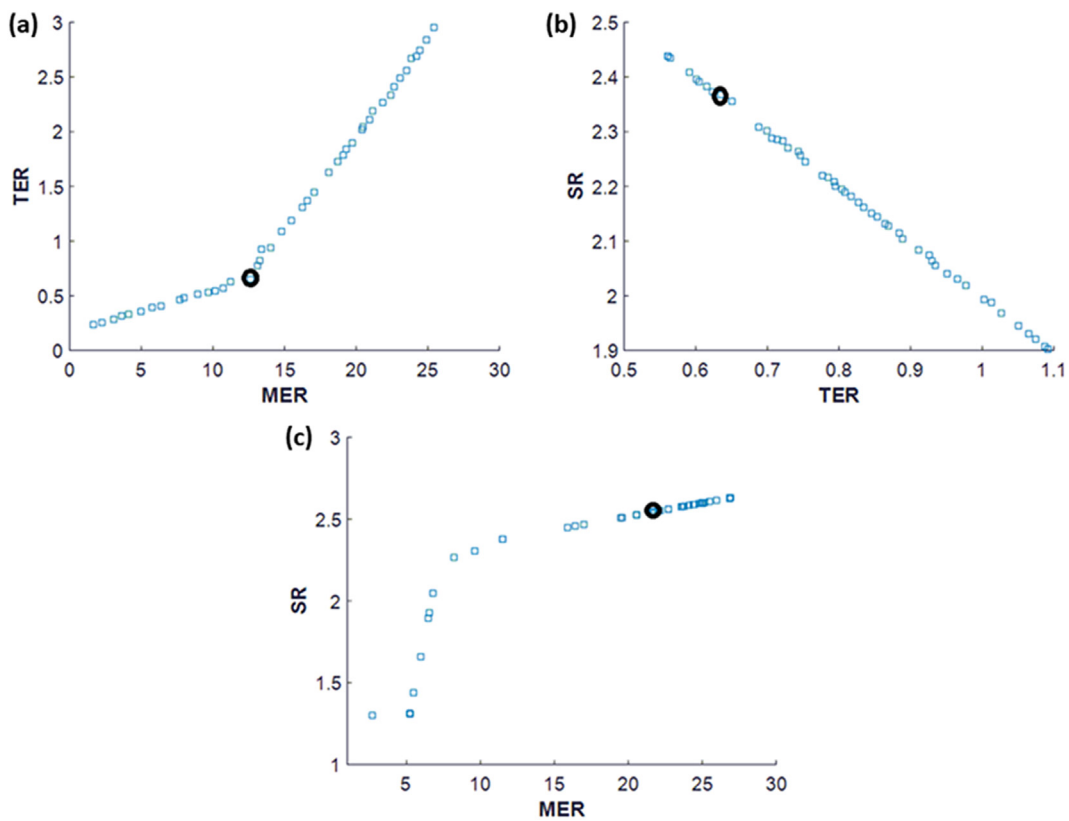


Fig. 14 – Pareto's optimal frontiers of (a) TER vs. MER, (b) SR vs. TER, (c) SR vs. MER.

when TER improves, SR does so. In terms of manufacturing, MER is favored for “larger is better”, whereas TER and SR are preferred for “smaller is better”. As a result, finding the proper combinations of EDM process factors that result in a big MER while having a low SR and TER is extremely challenging. For this study, the following two goals have been proposed:

$$\text{Objective}_1 = \text{Maximize } \{(\text{MER})\}$$

$$\text{Objective}_2 = \text{Minimize } \begin{cases} \text{TER} \\ \text{SR} \end{cases}$$

The MOSHO was used to predict 50 sets of the desired solution for each combination of responses that met the objectives. Figure 14a, b depicts the Pareto's optimal frontiers presenting the obtained sets of solution. Among 50 sets of the optimal solution, the finest seven optimal solution sets were selected and reported in Tables 7–9. The predicted sets of process variables were taken to conduct the confirmatory experiments to compare with the obtained solution sets, which were tabulated in the same tables. As the Pareto's frontier solution sets are the best data sets, any solution set can be picked based on the needs of the manufacturers.

According to the objective function, the replies (TER and MER) have opposing natures as shown in Fig. 14a. TER improves when MER augments. MER is increased from 1.42 mg/min to 25.42 mg/min, resulting in an increase in TER from 0.23 mg/min to 2.95 mg/min. As a result, if MER is regarded to be the top priority, TER must be harmed due to their contradictory behavior. The optimal solution set for TER and MER of 0.68 mg/min and 12.62 mg/min, respectively, is anticipated at 9.95 A current density, 8.15 μ s pulse-on time, 14.97/0.5 g/l HA/CNT quantity, and 45.2% duty cycle, based on the LINMAP technique. From Table 7, the computed confirmatory experimental errors are smaller than 10%, indicating that the projected data sets for MER and TER are highly accurate. Run #3 shows a low error for TER, while run #2 reveals a high error for it. Run #6 calculates a small error for MER, whereas run #4 gives a large error of 6.95% for it. Since the selective solution sets are included in Table 6, anyone can be used to get the desired responses.

In Fig. 14b, when TER improves, SR displays a declining trend. When a reduction in TER from 0.56 mg/min to 1.09 mg/min occurs, SR rises from 1.09 μ m to 2.43 μ m. According to the LINMAP approach, a current density of 5 A, discharge period of 8.02 μ s, HA/CNT quantity of 14.96/0.5 g/l, and duty cycle of 46.19% are the optimal combinations for SR and TER of 2.37 μ m and 0.62 mg/min, respectively. From Table 8, the estimated confirmatory test errors are smaller than 10%, implying that the SR and TER predicted data sets are highly accurate. For TER, run #5 reveals a low error, whereas run #4 shows a big error. For SR, run #1 measures a large error of 8.02% while an error of 1.38% is calculated for run #6. It is clearly seen that a high HA/CNT amount of 15/0.5 g/l is suggested to minimize both SR and TER.

Form Fig. 14c, the responses (SR and MER) are found to have contradictory natures when seen through the objective function. SR improves with increasing MER. MER is increased from 2.68 mg/min to 26.86 mg/min, leading to a rise of SR from 1.30 μ m to 2.62 μ m. If MER is regarded to be the top

Table 7 – Optimal solutions for minimizing TER and maximizing MER with confirmatory results.

Sl.no	Peak current	Pulse-on time	HA amount	Duty cycle	Predicted results		Experimental results		Error (%)	
					TER	MER	TER	MER	TER	MER
1	9.95 (10)	8.12 (8)	14.97	45.2	0.65	12.62	0.68	13.23	4.61	4.83
2	9.21 (9)	8.06 (8)	14.91	45.01	0.54	10.15	0.58	10.78	7.41	6.21
3	9.95 (10)	13.61	14.93	47.01	2.02	20.41	2.09	19.84	3.46	2.79
4	9.95 (10)	10.42	14.88	46.52	1.31	16.24	1.22	17.37	6.87	6.95
5	9.96 (10)	15.21	14.88	50.21	2.84	24.91	2.63	23.87	7.39	4.17
6	9.91 (10)	9.61	14.89	45.89	0.94	14.03	0.89	14.23	5.31	1.42
7	8.38 (8)	8.07 (8)	14.85	45.15	0.46	7.68	0.49	7.88	6.52	2.61

Note: Error = Abs(Predicted results - Experimental results)/Predicted results x 100%.

Table 8 – Optimal solutions for minimizing SR and minimizing TER with confirmatory results.

Sl.no	Peak current	Pulse-on time	HA amount	Duty cycle	Predicted results		Experimental results		Error (%)	
					SR	TER	SR	TER	SR	TER
1	5	8.02 (8)	14.96	46.19	2.37	0.62	2.18	0.66	8.02	6.5
2	5	8.02 (8)	14.99	54.98	1.91	1.09	1.86	1.02	2.61	6.4
3	5	8.02 (8)	14.97	45.01	2.43	0.56	2.33	0.59	4.11	5.4
4	5	8.02 (8)	14.98	49.36	2.21	0.79	2.26	0.72	2.26	8.9
5	5	8.01 (8)	15	51.95	2.06	0.93	2.19	0.89	6.31	4.1
6	5	8.01 (8)	14.97	50.16	2.16	0.83	2.13	0.87	1.38	4.8
7	5	8.02 (8)	14.96	51.84	2.1	0.92	2.18	0.88	3.81	4.3

Note: Error = Abs(Predicted results - Experimental results)/Predicted results x 100%.

Table 9 – Optimal solutions for minimizing SR and maximizing MER with confirmatory results.

Sl.no	Peak current	Pulse-on time	HA amount	Duty cycle	Predicted results		Experimental results		Error (%)	
					SR	MER	SR	MER	SR	MER
1	10	16	14.01	55	2.59	25	2.68	24.63	3.47	1.36
2	10	16	15	55	2.62	26.9	2.54	25.97	3.05	3.31
3	10	16	9.28	55	2.44	15.9	2.58	16.54	5.73	3.52
4	6.63 (7)	8	7	55	1.89	6.46	1.93	7.12	2.11	10.2
5	6.13 (6)	13.6	14.01	55	2.26	8.24	2.14	7.88	5.31	4.36
6	10	16	7	55	2.37	11.5	2.43	10.76	2.53	6.43
7	10	16	11.78	55	2.52	20.6	2.58	20.21	2.38	1.65

Note: Error = Abs(Predicted results - Experimental results)/Predicted results x 100%.

importance, SR must be harmed as a result of their contradictory behavior. The optimal solution set for SR and MER of 2.59 μm and 25 mg/min, respectively, is estimated at 10 A current density, 16 μs discharge period, 14.01/0.5 g/l HA/CNT quantity, and 55% duty cycle using the LINMAP approach. In Table 9, the estimated confirmatory test errors are lower than 10%, confirming that the projected data sets for MER and SR are highly accurate. For MER, run #1 provides a small error of 1.36%, whereas run #4 shows a large error of 10.2%. For SR, run #4 displays a small error of 2.11%, while run #3 shows a large error of 5.73%.

4. Conclusion and further study

In this research, the effects of adding CNT to the HA mixed-EDM process as well as EDM process parameters on machining responses including MER, SR and TER when fabricating the 316L steel were investigated. The following conclusions were drawn from statistical and SEM/EDX-based investigations.

1. Adding CNT 0.5 g/l in the HAp mixed-EDM process improves MER to 26.47 mg/min and reduces both SR and TER to 1.85 μm and 0.245 mg/min, respectively.
2. SEM spectrum confirms the machined surface with free of cracks and morphological features, such as nanopore, micropore and shallow craters. EDX spectrum ensures the presence of the employed materials on the machined surface.
3. Among the selected four EDM process factors, peak current, HA/CNT amount and pulse-on time show their influences on MER, SR and TER. However, duty cycle as a process variable does not show any impact on the responses in this study. The most important element for machining responses is peak current pursued by pulse-on time and HA/CNT quantity.
4. Through MOSHO technique, in total 50 sets of solution for each combination of the responses are obtained. A high discharge energy application with HA/CNT of 15/0.5 g/l is suggested to obtain a high MER and low TER, whereas a low discharge energy application with HA/CNT amount of 15/0.5 g/l is predicted for minimizing both SR and TER. The estimated confirmatory test errors are smaller than 10%, ensuring that the predicted solution sets are accurate.

This research has acknowledged a few limitations which should be addressed in the future works. For instances, the impacts of addition of more CNT quantity in the HA mixed-EDM process is still unknown. Future studies should address the thermal and electrical conductivity variations of the dielectric after it has been blended with the two additions.

Author contributions

Conceptualization, M.A.-A and A.M.A.-R; Methodology, M.A.-A; Software, M.A.-A, M.D, F.T.Z, R.A; Validation, S.R, S.A, R.A. and F.T.Z.; Formal analysis, M.A.-A and F.T.Z.; Investigation, M.D and M.S; Resources, M.A.-A; Data curation, M.A.-A, F.T.Z and

R.A.; Writing-original draft preparation, M.A.-A; Writing review and editing, A.M.A.-R, M.D. M.S; Visualization, S.A, M.S; Supervision, A.M.A.-R; project administration, A.M.A.-R; Funding acquisition, M.D. All authors have read and agreed to the published version of the manuscript.

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Informed consent statement

Not applicable.

Data availability statement

Not applicable.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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