Experimental Investigation and Multi-Objective Optimization of Cryogenically Cooled Near-Dry Wire-Cut EDM Using TOPSIS Technique

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Research Article

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Posted Date: April 26th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-254117/v1

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Experimental investigation and multi-objective optimization of cryogenically cooled near-dry wire-cut EDM using TOPSIS technique

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Abstract

In this research, the mixing of compressed air with the minimum quantity of water is used as a dielectric medium and the cryogenically cooled molybdenum wire is used as a tool in wire-cut electrical discharge machining (WEDM) to encourage the eco-friendly production, called cryogenically cooled near-dry WEDM process. The nitrogen gas-cooled wire tool is utilized to cut the Inconel 718 alloy workpiece to prevent wire breakage and maintain enough electrical conductivity. The preliminary experiments were conducted to compare wet, dry, near-dry, and cryogenically cooled near-dry WEDM processes. It was revealed that cryogenic cooled near-dry WEDM is better performance than dry, near-dry WEDM except for the wet process. The systematic experiments of eco-friendly cryogenically cooled near-dry WEDM have been conducted to analyse the effect of input factors like spark current, pulse-width, pulse-interval, and mixing water flow rate on material removal rate (MRR) and surface roughness (SR) using Box–Behnken method. The fitted models and response surface graphs were developed to analyse the influences of input factors on each response parameter. It was concluded that MRR and SR of cryogenically cooled near-dry WEDM are increased by maximizing spark current, pulse-width, and flow rate, conversely, both responses were decreased by increasing pulse-interval. The technique for order of preference by similarity to ideal solution (TOPSIS) technique has been applied to predict the best combination of input factors for satisfying the optimal values of both responses.

Keywords: wet; dry; near-dry; WEDM; cryogenically cooled wire; Inconel 718 alloy; Box–Behnken method; TOPSIS
1. Introduction

In the modern production industries, various unconventional manufacturing processes are utilized to machine the tough and complex shape of industrial parts. The wire-cut EDM is one of the indispensable machining processes to cut such materials[1]. The Inconel 718 alloy is used in manufacturing the parts of aircraft turbine engines, high-temperature fasteners, and cryogenic tanks due to high strength and corrosion-resistant properties[2–4]. As per ISO 14000, eco-friendly machining processes are promoted with high machining performances[5]. It was observed from the literature that harmful hazardous contaminants are emitted during the machining of various metals using EDM processes[6, 7]. In EDM /WEDM processes, the evaporation of dielectric fluid reacted with eroded different work materials, and mixing of dielectric fluid with atmospheric gases are affecting the health of the machine operators[8]. These harmful hazardous wastes have been minimized by changing machining processes, coolant fluid, and reducing machining time[9, 10]. Thus, the changes of the dielectric medium are trending to minimize the environmental impacts in EDM researches. Dry and near-dry EDM/WEDM processes are important efforts to enhance the eco-friendly machining atmosphere. In the dry EDM/WEDM processes, the pressurized air and gases (oxygen, helium, and argon gases) are used as the dielectric fluids in the place of the liquid medium[11–14]. The machining performance of the dry EDM/WEDM is low and unstable compared with conventional processes[15–18]. These downsides have been minimized by near-dry EDM and WEDM processes [10, 16, 19]. In the near-dry EDM/WEDM processes, the compressed air/gases mixed with the minimum amount of liquid/water are used as dielectric fluid[10, 13, 14, 18–22]. Many researchers have been attempted to enhance the near-dry EDM/WEDM processes. In the previous near-dry EDM/WEDM researches, assisting vibrations to electrodes and work materials, ionic gas as dielectric, powder mixed gas-mist dielectric, controlling spark gap, tool and workpiece orientations changes in EDM/WEDM experiments had been tried to enhance the machining performances[23–31].

The cryogenic treated conventional EDM and WEDM researches are deliberated as follows. The cryogenically cooled EDM experiment was performed using the copper tool to machine M2-steel material and material debris rate, wear ratio of the electrode, and surface irregularity has been studied. It was concluded that the tool wear ratio is 20% less than conventional EDM with a 27% of reduction of surface roughness[32]. The EDM characteristics using cryogenic treatment of the tool (copper and copper-chromium) and titanium workpiece have been studied with untreated EDM process using Taguchi method. 60.39% of MRR and 58.77% of TWR is
improved by cryogenic conventional EDM process[33]. The cryogenically treated copper and brass electrodes used in kerosene oil EDM experiments were performed to machine AISI D3 die steel to decrease the electrode wear percentage[34]. The experiments of the ultrasonic-assisted cryo-cooled copper tool EDM process have been performed to machine the M2-HSS to enhance the machining characteristics. It was revealed that ultrasonic-aided cryogenically chilled EDM improves the MRR with the recast of machined surfaces[35]. A comparative study was performed between cryogenic treated and untreated microelectrodes in micro-EDM to analyze the electrical resistance, crystallite dimensions, micro-hardness, and microscopic investigation. It was proved that the tool wear ratio (TWR) is significantly reduced to 51%, 58%, and 35% in brass, tungsten, and copper tool respectively[36]. Another attempt was made on conventional EDM for machining the AISI D2 tool steel by cryogenically cooled square copper electrode to reduce the electrode wear ratio (EWR) and surface irregularity. It was exposed that 20% of the tool wear was decreased with a good surface finish in cryo-treated EDM[37]. The next attempt is carried out to machine the AISI 304 stainless steel by cryogenically cooled liquid EDM process using the brass tool to study the EWR, MRR, and SR. It was observed that MRR is improved to 70%, EWR is reduced to 70% and surface roughness was reduced to 50%[38]. Recently, the effect of cryogenic treated and untreated tool on EDM tests have been performed out on Inconel-625 workpiece material. Influences of controlling factors on MRR and surface roughness have been investigated[39]. The electrode wear ratio and MRR were examined on a conventional EDM process using the TOPSIS approach[40]. The cryogenic treated and untreated copper are used as the electrodes to study the importance of rotational speed, voltage, and current on tool wear and SR while machining EN24 material. It was observed that 13.25% of tool wear and 15.75% in surface irregularity have been reduced by the cryogenically treated EDM process[41, 42]. Dimensional accuracy, tool wear rate, surface roughness, the material removal rate of cryogenic treated WEDM process have been investigated to find the best parameters[43]. As per the aforementioned literature, the cryogenic treated tools and workpieces were experimented with reducing the TWR, and SR, and increased the MRR by controlling various parameters in the conventional EDM and WEDM processes.

The first cryogenically cooled copper tool on the dry die-sinking EDM of titanium alloy has been performed to examine the influences of process parameters on EWR and SR. It was revealed that 27% of EWR was improved from the cryo-cooling effect of a tool than dry EDM with the betterment of surface finish[44]. The cryogenically cooled gases in the dry EDM
processes were carried out to machine the hard materials to improve the MRR to 50% and reduce the surface roughness to 10% compared with dry EDM\[45\]. It was observed that very few researchers were strived on applying the cryogenic assisted dry and near-dry EDM experiments to accomplish better machining performances. Very recently, the electric conductivity, wire wear resistance of molybdenum wire electrode has been improved by cryogenic treatment\[46, 47\]. However, as per the above literature, cryogenically cooled molybdenum WEDM experiments are yet not performed systematically.

Hence, there are no researches found in cryogenically cooled near-dry WEDM processes due to some technical difficulties during the cutting period. There were also no research attempts found in the cutting of Inconel alloy by cryo-cooled near-dry WEDM process. In this paper, the wet, dry, near-dry and cryogenically cooled near-dry WEDM processes have been compared in preliminary experiments. The systematic cryogenically cooled near-dry WEDM experiments have been performed to cut the Inconel 718 alloy material using the Box- Behnken method. The key concept of this research is to predict the best optimum solutions to meet best the industrial practices of production departments by the Box-Behnken which results as a source to TOPSIS approach.

2. Experimental setup

The billet size of 100 mm × 100 mm × 10 mm nickel-chromium alloy [Inconel 718 alloy] was taken as work material. The chemical compositions and mechanical attributes are shown in Tables 1 and 2 respectively. In this research, the fuzzy logic numerically controlled wire-cut electrical discharge machine was utilized to conduct all the experiments. Experimental visible of wet, dry, near-dry, and cryogenically cooled WEDM processes are exposed in Figures 1(a), (b), (c), and (d) respectively. The 10mm thickness of Inconel 718 alloy and 0.02mm diameter of Molybdenum wire is used as work material and electrode tool respectively. The dry, near-
dry, and cryogenically cooled near-dry setups have been additionally attached to the existing machine. The cutting parameters considered for the comparative studies are listed in Table 3.

<Insert Table 3 about here>

i. **Wet WEDM:** The experiments were conducted without making any changes to the existing machine (Figure 1(a)). The spark-current, pulse-width, and pulse interval are taken to conduct the preliminary experiments. The one-liter/min flow rate of demineralized water is used as a dielectric medium.

ii. **Dry WEDM:** Five bar pressure of compressed air has flowed as the dielectric fluid, which is passed into the plasma zone using nozzle (Figure 1(b)). The pressure is measured by a pressure gauge which is attached to the pneumatic experimental setup. MRR and SR are discrete processes. The spark-current, pulse-width, and pulse interval are taken to conduct the preliminary experiments. There is no liquid mixed with air.

iii. **Near-dry WEDM:** the minimum quantity of water mixed with five bar pressure of air is used as a dielectric fluid by a near-dry experimental setup[48, 49]. The near-dry WEDM experiments were steered by air-mist in the reciprocating WEDM machine (Figure 1(c)). The pressure is measured by a pressure gauge in the setup. The flow rate of mixing water is observed from the quantity of water collected about the time. The co-axial tubes are used to circulate water and air to the nozzle. At the end of the coaxial tubes, the water is atomized by compressed air. The nozzle is used to increase the velocity air-mist and to provide a cooling effect to the cutting zone. The debris is removed by the high velocity of air-mist from the machining zone. The spark-current, pulse width, pulse interval, and flow rate are considered to perform preliminary experiments.

iv. **Cryogenically cooled near-dry WEDM:** The same near-dry experimental setup was used to conduct the cryogenically cooled near-dry WEDM experiments and additionally, the wire tool is cooled by N₂ gas (Figure 1(d)). The schematic layout of the experimentation is shown in Figure 4. Below -150°C temperature of liquid nitrogen was stored and maintained in a Dewar flask. On both sides of the workpiece, the molybdenum wire was cryogenically cooled by two short hoses. The cryo-cooled near-dry WEDM experimental setup is shown in Figure 5. The spark-current, pulse-width, pulse interval, and flow rate are considered to conduct the preliminary experiments.
The spark current, pulse-width, and pulse interval can be controlled by a control panel setup in the WEDM machine. The surface roughness was directly measured by the Mitutoyo-SJ-201P surface tester (0.01 µm resolution). Surface roughness was measured along four times linear movement of stylus travel over the workpiece surface and the average values are considered. Material removal rate (MRR) is determined by the ratio of the quantity of removed material with the specified period the equation (1).

\[ MRR = \frac{(w \times l \times k)}{t} \text{ mm}^3/\text{min} \quad (1) \]

Where,

\[ w \] - width of the workpiece in mm (3 mm)

\[ l \] - length of cut in mm (10 mm)

\[ k \] - (kerf) wire diameter+2 times of spark gap, in mm,

\[ = 0.18 \text{ mm}+ 2\times0.01 \text{ mm} = 0.20 \text{ mm} \]

\[ t \] - time for the same length of the cut, in minutes.

The preliminary experiments were performed by one variable at a time method[10, 14]. In this approach, only one variable is changed to observe the effect on responses, and all other factors are kept continuous in their middle level.

3. Preliminary experiments comparative analysis

The variations on MRR by the influences of spark current, pulse width, pulse interval, and flow rate are illustrated in Figures 2(a), (b), (c), and (d) respectively. The input factors (spark current, pulse width, pulse interval, and mixing flow rate) effect on MRR of near-dry, and cryogenically cooled near-dry WEDM processes are lower than conventional WEDM. similarly, the variations on SR concerning the changes of spark current, pulse-width, pulse-interval, and flow rate are displayed in Figures 3(a), (b), (c), and (d) respectively. The input factor's effect on SR of dry, near-dry, and cryogenically cooled near-dry WEDM processes are better than conventional WEDM. The influence of flow rate on MRR and SR of near-dry, and cryogenically cooled near-dry WEDM (except dry and wet processes) are illustrated in Figures 2(d) and 3(d).

(a) Wet WEDM process: The MRR and SR are linearly increased by increasing the spark current, and pulse width, conversely, decreased by an increase in pulse interval. The 0.8ml of flow rate is constantly maintained. It was also observed that MRR and SR are higher than the other three conditions.
(b) **Dry WEDM Process:** In the dry WEDM process, stick the work materials with wire to at the high values of controlling parameters due to insufficient dielectric strength and short circuit issues\[50–52\]. The wire-work piece sticking, discrete sparks, insufficient heat energy, and unstable cutting problems are significant problems observed during the dry WEDM process. The surface roughness of the dry WEDM is higher than the near-dry WEDM process due to the above-mentioned problems \[53\]. However, SR of dry WEDM is better than conventional WEDM due to the small depth of crater caused by air \[53\].

(c) **Near-dry WEDM process:** In the near-dry WEDM process, MRR and SR responses are stable than the dry process. The near-dry WEDM is one of the proven methods to overcome the drawbacks in the dry process\[49, 54\]. The MRR and SR are gradually increased by increasing the spark current pulse width and mixing water flow rate, conversely, decreased by an increase in pulse interval. However, MRR is deprived and SR is better than wet WEDM due to due to small depth of crater by air-mist\[53, 55\].

(d) **Cryogenically cooled near-dry WEDM process:** It was revealed that the input factors behaviour on responses is similar to the near-dry WEDM process. The surface finish of cryogenically cooled near-dry process better results than wet, dry, and near-dry WEDM process due to increase in cooling effect, the dielectric strength of cooled wire\[41, 56\]. It is improved by regular and uniform surface topology due to reducing reattachment overcutting surfaces\[56\]. However, its MRR is slightly lower than the wet WEDM process and is better than dry and near-dry WEDM processes.

Hence, the surface finish of the cryogenically cooled process is better than the other three conditions (Figures 3(a), (b), (c) and (d)). Many parameter optimization studies of the wet WEDM process have been elaborated and the dry WEDM process is unstable. To promoting an eco-friendly machining process, the cryogenic near-dry WEDM has been considered for systematic studies using Box- Behnken method and TOPSIS analysis.

<Insert Table 4 about here>

<Insert Figure 2 about here>
4. Design of Experiments for Cryogenically cooled near-dry WEDM using Box-Behnken method

Box–Behnken design of experiment is used to conduct 29 trials. It is a self-determining quadratic design, which does not contain the partial factorial design. It has restricted capability related to the central composite designs. The cryogenically cooled near-dry WEDM input factors and their levels are shown in Table 4. Five central points are repeated to avoid bias error. It uses 8 trails from \((2 \times 4 = 8)\) two levels of \(K^h\) parameters, 16 trails of two factorial design \((2^4 = 8)\), and five repeated central points to calculate lack-of-fit. 29 sets of experiments were conducted and observed responses are presented in Table 5. Based on the ANOVA test, the significant individual, interaction, and quadratic terms were identified[57]. Insignificant terms are eliminated from the model. If the response is \(f(x)\), the independent variables are \(x_1, x_2, x_3, x_4, \ldots x_n\), the response model is developed by following a general equation[57] (2).

\[
    f(x) = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j + \ldots + \emptyset \quad i < j
\]

(2)

Where ‘\(K\)’ is the numeral of process variables, ‘\(\beta_0\)’, ‘\(\beta_i\)’, and ‘\(\beta_{ij}\)’, are the model coefficients and ‘\(\emptyset\)’ is the model error, which characterizes variability by other noises.

<Insert Table 5 about here>

5. Multi-objective optimization using TOPSIS technique

TOPSIS is a multi-criteria decision-making tool that is applied to predict the best solution among a great number of alternatives. The alternative which has the highest distance from the Negative Ideal Solution (NIS) and the shortest distance from Positive Ideal Solution (PIS) will be selected as best. In TOPSIS, the response parameter to be maximized is considered as the beneficial attribute, and the response to be minimized is considered as a non-beneficial attribute[58, 59]. The steps of TOPSIS are explained as follows.

Step 1: The decision matrix is to be constructed with response data. The decision matrix (equation 3) should contain the ‘\(n\)’ number of attributes and ‘\(m\)’ number of alternatives solutions. Here, the attribute denotes the various responses and the alternative solution denotes the experimental trials[58].

\[
    D = \begin{bmatrix}
    a_{11} & a_{12} & \cdots & a_{1n} \\
    a_{21} & a_{22} & \cdots & a_{21} \\
    \vdots & \vdots & \ddots & \vdots \\
    a_{m1} & a_{m1} & \cdots & a_{mn}
    \end{bmatrix}
\]

(3)
Step 2: Each attribute own data in different ranges, hence normalization is to be done to convert the range of data between 0 and 1 for easy calculation using equation 4.

$$N_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} a_{ij}^2}}$$  \hspace{1cm} (4)

Where $N_{ij}$ is the normalized value for $i=1, 2, \ldots, m$ and $j=1, 2, \ldots, n$.

Step 3: Weighted normalized matrix (equation 5) is calculated by assigning appropriate weights to each attribute. Always, the sum of weights should be equal to 1[58].

$$\delta_{ij} = W_j \times N_{ij}$$  \hspace{1cm} (5)

Where $\sum_{j=1}^{n} W_j = 1$

Step 4: PIS and NIS from weight normalized matrix are determined by equations (6) and (7)

$$\delta^+ = (\delta_{1}^+, \delta_{2}^+, \ldots, \delta_{n}^+) = \left\{ \begin{array}{l} \left( \max \delta_{ij} \ | j \in J_1 \right) \\ \left( \min \delta_{ij} \ | j \in J_2, i = 1,2,\ldots \right) \end{array} \right.$$  \hspace{1cm} (6)

$$\delta^- = (\delta_{1}^-, \delta_{2}^-, \ldots, \delta_{n}^-) = \left\{ \begin{array}{l} \left( \min \delta_{ij} \ | j \in J_1 \right) \\ \left( \max \delta_{ij} \ | j \in J_2, \right) \end{array} \right.$$  \hspace{1cm} (7)

Where $J_1$ belongs to beneficial attribute, $J_2$ belongs to non-beneficial attribute and $i=1, 2, 3\ldots, n$.

Step 5: Euclidian distance of each alternative from ideal solutions is calculated by equations (8) and (9).

$$S_{i}^+ = \sqrt{\sum_{j=1}^{1} (\delta_{ij} - \delta^+)^2}$$  \hspace{1cm} (8)

$$S_{i}^- = \sqrt{\sum_{j=1}^{1} (\delta_{ij} - \delta^-)^2}$$  \hspace{1cm} (9)

Where $i=1, 2, \ldots, m$.

Step 6: the closeness coefficient of each alternative key is calculated by equation (10).

$$CC = \frac{s_{i}^-}{S_{i}^+ - s_{i}^-}$$  \hspace{1cm} (10)
6. Results and Discussions
6.1. Response surface analysis using Box-Behnken method

The Analysis of variance test of MRR and SR concerning process parameters are shown in Tables 6 and 7. The regression models of MRR and SR were developed and shown in equations (11) and (12) respectively.

\[
MRR = -8.241 + 5.335 \times C + 0.45 \times PW - 0.065 \times PI - 0.0575 \times F - 0.0595 \times C \times PW + 3.5 \times 10^{-3} \times C \times PI + 0.04 \times C \times F - 0.425 \times C^2
\]

\[
SR = -1.958 + 1.8542 \times C + 0.227 \times PW - 0.0226 \times PI + 6 \times 10^{-3} \times F - 0.074500 \times C \times PW + 2.17 \times 10^{-3} \times PW \times PI - 8.3 \times 10^{-4} \times PI \times F - 4.821 \times 10^{-4} \times PI^2
\]

\[
R^2 = 99.40\% \quad \text{Adjusted } R^2 = 99.14\% \quad \text{Predicted } R^2 = 98.18\%
\]

\[
R^2 = 99.39\% \quad \text{Adjusted } R^2 = 99.15\% \quad \text{Predicted } R^2 = 99.04\%
\]

The insignificant terms were eliminated from MRR and SR regression models to improve the predicted \( R^2 \) and adjusted \( R^2 \) values. The regression models are used to plot the response surface between response and input factors. The influences of the interaction effects of input parameters have been studied by the response surfaces.

The percentage of contribution of spark current, pulse width, pulse interval, and flow rate on MRR is 52.92\%, 24.63\%, 12.81\%, 5.75\% respectively. The MRR is improved by the heating, melting, evaporating of the materials and high energy density of spat plasma channel by current while increasing spark intensity and spark current between work materials and wire[60, 61]. The response surface of MRR for spark current and pulse-width is displayed in Figure 6(a). It was revealed that the MRR is improved by easy expanding and migrating plasma channel, energy density, and minimum resistance to expansion of spark while increasing pulse duration in the air-mist medium[61, 62]. Figure 6(b) shows that the response surface of MRR by the flow rate vs spark current. It is also significantly enhanced by increasing the flushing efficiency.
and due to the quick disposal of debris from the cutting zone[63]. For the plot the response surface plot between C and PI (Figure 6(c)), C×PI interaction terms are included even if it is insignificant[10, 64]. The MRR is increased by reducing pulse interval due to an increase in spark pause time.

<Insert Figures 6 (a), (b) and (c) about here>

<Insert Figures 7 (a), (b) and (c) about here>

The minimization of surface roughness is one of the goals of this study. SR of cryogenically cooled near-dry WEDM is better than the other three conditions due to the small depth of crater by air-mist[53, 55]. The percentage of contribution of spark current, pulse width, pulse interval, and flow rate on SR is 14.89%, 9.77%, 62.18%, and 5.44% respectively. The SR is minimum at the low value of pulse interval and pulse width due to fine and soft spark in the cutting zone as shown in Figure 7(a). The increase in pulse interval is increasing the SR due to the narrow plasma channel at low pulse interval[61]. is significantly increased, the surface roughness is least due to small depth of crater, while decreasing pulse width, the spark current[53, 55]. Figure 7(b) showed the interaction effects of pulse width and spark current on SR. While increasing the spark current, the SR is exploiting due to the highest debris by high spark intensity in the plasma channel[61]. The surface roughness is getting reduced by increasing flushing efficiency while increasing flow rate[65, 66]. However, SR is also slightly increased by growing MRR by fast flushing debris (Figure 7(c)).

However, the MRR and SR are conflicting responses from the view of customer expectations. The expectation of the customer is the trade-off between the maximize the MRR and minimize the SR. The individual factor response surface analysis is unable to satisfy customer expectations to select the optimal input factors for the best of both responses. To overcome this difficulty, the TOPSIS technique is applied to select the combination of input factors for best both responses.

6.2. TOPSIS Analysis

In single-objective optimization, the different optimum parameter has been obtained for each response MRR and SR. In the real-time scenario, uncertainty will be created to select the proper input process parameter, as both the response are equally important while machining. To overcome the difficulty, a multi-objective optimization method can be utilized and among various techniques, TOPSIS is one of the simple and effective methods. TOPSIS converts the multi-objective problem into the single objective problem by joining the responses with proper
weightage [22]. As mentioned earlier, the MRR and surface roughness are equally important in machining, hence equal weightage has been assigned for converting into the single-objective problem.

Initially, the decision matrix was normalized to convert the range of data between 0 and 1 for easy calculation. The normalization was done using equation (4). Followed by normalization, weightage has to be assigned to each response based on its importance. While machining a material in industries, more material should be removed without compromising surface finish to reduce machining time. Hence the equal weight (50%) was assigned to MRR and SR, and the weighted normalized matrix was calculated using equation (5). Since the MRR is to be maximized, the PIS is the maximum value and NIS is the minimum value of the weighted normalized matrix. Whereas surface roughness is to be minimized, PIS is the minimum value and NIS is the maximum value of the weighted normalized matrix. \( \delta_M^{+} = 0.113, \delta_M^{-} = 0.0624, \delta_{SR}^{+} = 0.05 \) and \( \delta_{SR}^{-} = 0.124 \) are the calculated PIS (equation 6) and NIS (equation 7) of MRR and SR respectively. The separation measures of each attribute were calculated using equations 8 and 9. The closeness coefficient was calculated using equation (10). Table 8 shows all data calculated related to the TOPSIS technique.

The closeness coefficient was used to rank the alternative solutions in descending order. The experiment with the maximum closeness coefficient is measured as the best alternative solution and the experiment with the lowest closeness coefficient is considered as the worst alternative solution. Experiment number 17 possesses the highest closeness coefficient value of 0.758 and is considered the best alternative. Experiment number 4 has the lowest closeness coefficient of 0.332 and is considered as the worst alternative solution. Hence, the process parameter about experiment no 17 is considered as best among the conducted experiments. This indicates that experiment no 17 combined yield maximum MRR and minimum SR. The effect of each input factor on the closeness coefficient is exposed in Figures 8 (a), (b), and (c). The influence of pulse-width and pulse interval on closeness coefficient is demonstrated in Figure 8 (a). The closeness coefficient possesses a positive trend with PI and PW individually i.e., the increase in the value of PI and PW growths the closeness coefficient. Whereas, closeness coefficient behaves differently with the interaction of both parameters. The higher closeness coefficient is obtained for a minimum pulse interval and a maximum pulse-width, and vice versa. The
minimum value of both current and pulse-width and the maximum of the value of both yield a lower closeness coefficient. While interacting with pulse-width and current, these have performed as shown in Figure 8 (b). The closeness coefficient increases with an increase in the current while interacting with pulse-width. Figure 8(c) demonstrates that the interaction effect of pulse-interval and flow rate shows a momentous effect on the closeness coefficient. It indicates that the combined effect of parameters pulse-interval and flow rate also possess a noticeable effect on the closeness coefficient.

<Insert Table 9 about here>

The validation tests were accomplished to confirm the predicted optimum input factors for best MRR and SR as shown in Table 9. Hance, obtained results were closest to values from the test. The current 4 Ampere, pulse width 20µs, pulse interval 75µs, and 20ml/min flow rate gives 8.7 mm$^3$/min of MRR and 1.8 µm of SR.

7. Conclusions

It was revealed from preliminary experiments that cryogenically cooled near-dry WEDM is better performance than dry, near-dry WEDM except for the conventional dielectric process. Even if the wet WEDM process has better machining performance, the near-dry WEDM is one of the proven methods to enhance the eco-friendly machining process. Hence, the cryogenically cooled near-dry WEDM is called an improved near-dry WEDM process. It was proved that it is a stable process to cut the hard materials by systematic experiments.

It was concluded from Box-Behnken analysis that MRR and SR of cryogenically cooled near-dry WEDM are increased by maximizing pulse-width, current, and Flow rate, conversely, both responses were decreased by increasing pulse-interval. The machining performances have been improved by increasing the electrical conductivity of cryogenically cooling molybdenum wire during the cutting process. The spark current and pulse-width are the most significant factors for MRR. Increasing the spark-current and pulse width, the material removal rate is enhanced and SR is reduced. While increasing pulse-interval from 45µs to 75µs, both the material removal rate and surface roughness were decreased. The surface finish has been significantly improved at the dielectric fluid flow rate of 20 ml/min. The percentage of contribution of spark current, pulse width, pulse interval, and flow rate on MRR is 52.92%, 24.63%, 12.81%, 5.75% respectively. The percentage of contribution of spark current, pulse width, pulse interval, and flow rate on SR is 14.89%, 9.77%, 62.18%, and 5.44% respectively.
For the customer expectation, the TOPSIS technique was applied to predict the best combination of input factors for solutions to meet the best solution of conflict behaviour of MRR and SR. The 4 amperes of spark current, 20µs of pulse width, 75µs of pulse interval, and 20ml/min of flow rate are the optimum parameter set for best of MRR (8.7 mm³/min) and SR (1.8 µm). The multi-optimization results were validated using confirmation experiments.

Acknowledgment Author

The authors thank Mechanical Engineering at Bannariamman Institute of Technology, sathayamanagalam, Erode, Tamilnadu, India. for helping to carry out this research work.

Ethics approval:
Not Applicable

Consent to participate:
Not Applicable

Consent for publication:
Not Applicable

Authors Contributions:
Dr. Boopathi S contributed to conducting experiments, design of experiments, analyzing and interpreting the data regarding the near-dry WEDM Process.

Mr. Sureshkumar. M contributed in conducting experiments, design of experiments, analyzing and interpreting the data regarding the near-dry WEDM process.

Dr. Sudhagar S contributed to analyzing and interpreting the data from the TOPSIS approach with the near-dry WEDM process.

Funding:
No fund received.

Competing Interests:
The author declares that he has no competing interests.

Availability of data and materials:
The datasets generated during and/or analyzed during the current study are available from the corresponding author and included in this article.

Reference

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Figures

(a) Wet WEDM  
(b) Dry WEDM

(c) Near-dry WEDM  
(d) Cryogenically cooled Near-dry WEDM

Figure 1

Preliminary experimental setup for wet, dry, near-dry and cryogenically cooled near-dry WEDM
Figure 2

Preliminary experiments: Effects of parameters on MRR of wet, dry, near-dry and cryogenically cooled near-dry WEDM processes
Figure 3

Preliminary experiments: Effects of parameters on SR of wet, dry, near-dry and cryogenically cooled near-dry WEDM processes
Figure 4

Schematic diagram of the hydro-pneumatic circuit for cryogenically cooled near-dry WEDM
Figure 5

Experimental setup for cryogenically cooled near dry WEDM process
Figure 6

(a). Response surface for MRR concerning pulse width and spark current. (b) Response surface for MRR concerning Flow rate and spark current. (c). Response surface for MRR concerning spark current and pulse interval
Figure 7

(a). Response surface for surface roughness concerning Pulse width and pulse interval. (b). Response surface for surface roughness concerning Pulse width and current. (c). Response surface for surface roughness concerning Flow rate and pulse interval.
Figure 8

(a). Response surface plot for closeness coefficient concerning Pulse Interval and Pulse Width. (b) Response surface plot for closeness coefficient concerning Pulse width and current. (c). Response surface plot for closeness coefficient concerning Flow Rate and Pulse Interval.