Experimental Investigation of a Cryogenically Cooled Oxygen-mist Near-dry Wire-cut Electrical Discharge Machining Process

Boopathi Sampath[1,*] – Sureshkumar Myilsamy[2]

[1]Muthayammal Engineering College, Department of Mechanical Engineering, India
[2]Bannari Amman Institute of Technology, Department of Mechanical Engineering, India

In this paper, a novel method of cryogenically cooled (low-temperature nitrogen gas) wire tool is used during the oxygen-mist near-dry wire-cut electrical discharge machining (NDWEDM) process to cut Inconel 718 alloy material. The current, pulse-width, pulse-interval, and flow rate are the controllable variables for response characteristics, such as the material removal rate (MRR) and wire wear ratio (WWR). The Box-Behnken method is applied to design the experiments to collect the observations from experiments. The mathematical models for each response were developed using significant individual, interaction, and quadratic terms by the sequential sum of the square test. The response surfaces were developed. It was revealed from the analysis that 52.92 % of current, 24.63 % of Pulse-width, 12.81 % of pulse- interval and 5.75 % of flow rate contributed to MRR, while 14.89 % of current, 9.75 % of pulse-width, 62.20 % of pulse-interval, and 5.44 % of flow rate contributed to WWR. The pulse-width has more contribution on MRR due to the long period of spark between the wire and work materials. It was also observed that the pulse-interval has more effect on WWR due to the more ideal period (high spark-pause-time) between two consecutive high-temperature sparks in the wire tool. The wear of the wire tool has been analysed using scanning electron microscopy (SEM) photographs. The desirability principles were first applied to obtain multi-objective solutions with a combination of process parameters to achieve the optimal values of both responses. The predicted combination of results has been validated by data that were collected from confirmation experiments.
Keywords: cryogenically cooled, oxygen-mist, near-dry, wire-cut EDM, MRR, WWR, Box-Behnken method

Highlights
- *A novel method of cryogenically cooled (low-temperature nitrogen gas) wire electrode tool in the oxygen-mist near-dry wire-cut electrical discharge machining (NDWEDM) process was experimented with to cut the Inconel 718 alloy material.*
- *Wire wear ratio and material removal rate of cryogenically cooled near-dry WEDM process was first investigated in this research.*
- *It was revealed that the pulse-interval has more effect on wire wear ratio due to a more ideal period (high spark-pause-time) between two consecutive high-temperature spark in the wire tool.*
- *The wear of the wire tool has been analysed using Scanning Electron Microscopy test photographs.*
- *The desirability principles were first applied to obtain the multi-objective solutions to optimize both responses.*

0 INTRODUCTION

In an unconventional machining process, the relationships between manufacturing parameters and environmental impact are developed to analyse the material removal mechanics, tool change, minimum rejections in production, and the effects of cutting-fluid flow [1]. The environmental impact of machining processes should be analysed for minimizing environmental impacts by the modification of existing technology and the development of new manufacturing methods [2]. In these aspects, research into the modification of EDM and WEDM processes was developed to make a trade-off between machining performance and machining pollutions [3]. The analytical relationship of EDM processes was developed to reveal the wear of the tool and workpiece, the dielectric fluid flows, and toxicity and flammability [3] and [4]. The inferences of cooling electrode wear and surface roughness of the workpiece have been investigated by changing process parameters, such as voltage, pulse-width, current, and

pulse-interval [5] and [6]. The parametric analysis of dry electric discharge machining of mild steel was investigated, and response models were developed using response surface methodology [7]. Generally, the machining performance of the dry EDM process is very low compared to the conventional process. It was revealed that the tool wear of the dry EDM process is significantly reduced by cryogenic cooling of the electrode and workpiece [8]. The mechanism of the gas-liquid-powder mixture in EDM was investigated in both dry and near-dry processes to improve material erosion. The cryogenically tested brass wire produces a 22.55 % greater material removal rate (MRR) compared to an untreated brass wire [9]. A parametric study was performed using a molybdenum wire tool and tool steel workpiece with an air dielectric to investigate the influence of air-mist pressure, voltage, pulse-duration, pulse-width, and current on the MRR and Ra using the Taguchi technique [5] and [10]. Later, the oxygen gas near-dry WEDM experiments were conducted using Taguchi's L27 orthogonal array and multi-objective artificial bee colony (MOABC)

algorithm [11] and [12]. Cryo-treated wire electrodes, liquid nitrogen, and zinc-coated brass wires were investigated to reduce the tool wear rate for the green environment [4], [13] to [15]. Recently, the electrical conductivity of cryo-cooled molybdenum wire has been increased by cryogenic treatments [16]. However, no synchronized cryo-treated gas-liquid mixer was found in the near-dry EDM and WEDM process.

In this research, the data from 29 observations from cryogenically cooled oxygen-mist near-dry WEDM experiments were collected. The collected data are used to predict the data for better results of the near-dry WEDM process. The significant process parameters were identified to improve the quality of cutting processes. The desirability approach is used to convert the single-objective problem into a multi-objective optimization problem. The WEDM machine manufacturer and operators utilize the optimum results to set the optimal process parameters for the best machining performances.

1 EXPERIMENTATION

1.1 Experimental Setup

The cryo-cooled wire electrode setup was developed in numerically controlled (NC) wire-cut electrical discharge machining. Liquid nitrogen was stored in a dewar flask to maintain the cryogenic temperature. The molybdenum wire was cooled on both sides of the electrode movements. The oxygen and dielectric fluid mixture are used as a working medium in the reciprocating WEDM machine. Based on trial experiments, the input parameters and their significance levels are identified. The billet size of 718 is 50 mm × 50 mm × 5 mm Inconel 718 is used as work material for near-dry WEDM machining processes. The experimental setup of cryo-cooled near-dry WEDM is shown in Fig. 1. Sub-123 K of liquid nitrogen was stored. The 253 K temperature and 10 g/s mass flow rate of N_2 were used to cool the molybdenum wire during the cutting process. The

oxygen and the dielectric fluid mixture were used as a dielectric medium in reciprocating the WEDM machine. The MRR in [mm³/min] can be calculated by the volume of materials removed concerning time using Eqs. (1) and (2).

$$Kerf = wire\ diameter \times (2 \times sparking\ gap), \quad (1)$$

$$MRR = \frac{thickness \times Kerf \times length\ of\ cut}{time}. \quad (2)$$

The wire wear ratio (WWR) has been measured from the loss of wire materials during the cutting process concerning the time, and the initial weight of wire is to be taken before machining process [17] (Eq. (3)).

$$WWR = \frac{weight\ loss\ of\ wire}{initial\ weight\ of\ wire}. \quad (3)$$

Based on exploratory experiments, the input parameters and their significance levels are identified. The levels of each process variable are tabulated in Table 1. The near-dry WEDM experiments are conducted [18], and the MRR and WWR values observed through the experiments are shown in Table 2.
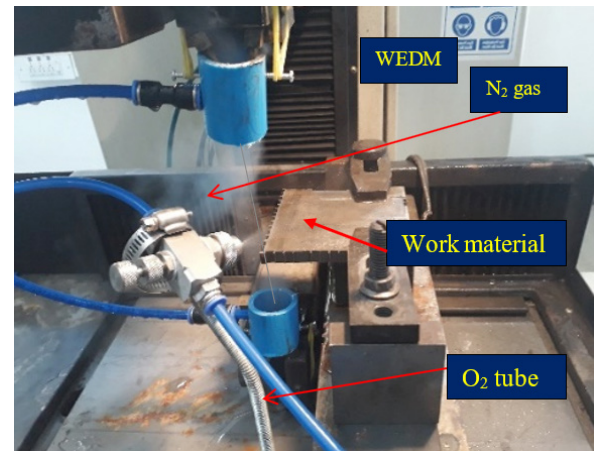

Fig. 1. *Cryogenically cooled oxygen-mist near-dry WEDM experimental set*

Table 1. *Parameter and Machine Setting level*

Description	Symbol	Parameter	Units	Low	High	Mean
Input parameters	C	Current	A	3	5	4
	PW	Pulse-width	μs	15	25	20
	PI	Pulse-interval	μs	45	75	60
	F	Flow rate	ml/min	10	20	15
Dielectric medium		Oxygen gas mixed with water				
Wire treatment		Cryogenic Nitrogen gas during the machining process				
Output parameters		MRR in [mm³/min], and WWR				

Table 2. *Design of Experiments and observations using Box–Behnken method*

Exp. No.	C	PW	PI	F	MRR	WWR
1	3	20	75	15	6.13	0.464
2	5	20	75	15	9.45	0.626
3	4	15	60	20	8.38	0.643
4	4	20	45	10	9.28	0.994
5	4	25	60	10	9.57	0.921
6	4	20	60	15	9.12	0.783
7	4	20	60	15	9.09	0.724
8	4	15	75	15	7.12	0.424
9	5	20	60	20	10.9	0.829
10	3	25	60	15	8.51	0.864
11	3	20	60	10	6.58	0.745
12	4	25	45	15	10.91	0.991
13	4	20	75	10	7.78	0.635
14	3	20	45	15	7.76	0.848
15	4	15	60	10	7.38	0.767
16	4	15	45	15	8.67	0.921
17	4	20	75	20	8.74	0.478
18	5	20	45	15	10.87	1.050
19	5	20	60	10	9.44	0.934
20	4	25	75	15	9.38	0.670
21	5	25	60	15	10.77	0.872
22	4	20	45	20	10.29	0.905
23	5	15	60	15	9.47	0.913
24	4	20	60	15	9.12	0.778
25	4	20	60	15	9.11	0.78
26	4	25	60	20	10.63	0.807
27	4	20	60	15	8.77	0.772
28	3	15	60	15	6.02	0.502
29	3	20	60	20	7.24	0.621

1.2 Design of Experiments

The Box-Behnken method is used to conduct the experiments by design expert software. The Box-Behnken design is a self-determining quadratic design, which does not contain the partial factorial design. The designs have restricted capability related to the central composite designs. Five central points are repeated to avoid bios errors. The design uses 8 trails from $(2 \times 4 = 8)$ two levels of k parameters, 16 trails of two factorial design $(24 = 8)$, and five repeated central points to calculate lack-of-fit. Twenty-nine sets of experiments were conducted, and the observed responses are tabulated in Table 2. Based on the analysis of the variance test, the significant individual and interaction and quadratic terms were identified [5]. Insignificant terms are eliminated from the model.

If the response is '$f(x)$', the independent variables are $x_1, x_2, \ldots, x_n$, and the response model is developed by following general Eq. (4).

$$f(x) = \beta_0 + \sum_{i=1}^{k} \beta_0 x_i + \sum_{i=1}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j + \ldots + \phi,$$

$$\text{and } i < j, \quad (4)$$

where k is the number of process variables; β_0, β_i, and β_{ij} are the model coefficients; ϕ is the statistical error, which represents variability by other noises.

2 RESULT ANALYSIS AND DISCUSSIONS

The sequential sum of the square test was used to select the optimum model for the analysis. Initially, the linear model is selected [12]. However, the model is not significant due to the coefficient of determination (R^2)

value of *MRR* and *WWR* is very low (*MRR* R^2 =0.072 and *WWR* R^2 = 0.81). The two factors interaction model (*2FI*) also did not fit with the solution due to the R^2 value of both models is minimum (*MRR* R^2 = 0.608 and *WWR* R^2 = 0.075). Then, the quadratic model of *MRR* was selected due to the R^2 value of 0.998 of both responses. The insignificant terms of the models were eliminated from quadratic models. The lack of fit of the model is insignificant and thus acceptable. The cubic models of both responses were not selected due to more allies' terms in the models. The lack of fit tests of *MRR* and *WWR* are shown in Tables 3 and 5, respectively. The analysis of the variations of *MRR* and *WWR* concerning process parameters are shown in Tables 4 and 6, respectively. The regression models of *MRR* and *WWR* were developed to identify the inference of process variables as shown in Eqs. (5) and (6) respectively.

$$
\begin{aligned}
MRR = &-8.241 + 5.335 \times C + 0.45 \times PW - 0.065 \times PI \\
&-0.0575 \times F - 0.0595 \times C \times PW \\
&+3.5 \times 10^{-3} \times C \times PI + 0.04 \times C \times F \\
&-0.425 \times C^2,
\end{aligned}
\tag{5}
$$

R^2 = 99.40 %, Adjusted R^2 = 99.14 %, and Predicted R^2 = 98.18 %.

$$
\begin{aligned}
WWR = &-0.529 + 0.501 \times C + 0.061 \times PW \\
&-6.161 \times 10^{-3} \times PI + 1.727 \times 10^{-3} \times F \\
&-0.0201 \times C \times PW + 5.867 \times 10^{-4} \times PW \times PI \\
&-2.267 \times 10^{-4} \times PI \times F - 1.298 \times 10^{-4} \times PI^2,
\end{aligned}
\tag{6}
$$

R^2 = 99.40 % , Adjusted R^2 = 99.16 %, and Predicted R^2 = 99.04 %.

The insignificant terms are eliminated from *MRR* and *WWR* regression models to improve the predicted R^2 and adjusted R^2. The regression models are used to plot the response surface between response and process variables. The influences of the interaction effects of process parameters have been studied using the response surfaces.

The response surface of *MRR* for flow rate and current is shown in Fig. 2. It is also significantly enhanced by increasing the flushing flow rate due to the quick disposal of debris from the cutting zone. Fig. 3 shows that the response surface of *MRR* by the pulse-width vs current. The *MRR* is improved by the increase in spark current between work materials and wire due to high spark strength [19]. It was observed that the large increase in *MRR* is seen from low pulse-width to high value by enhancing spark strength, as shown in Fig. 4 [12]. However, the *MRR* is increased

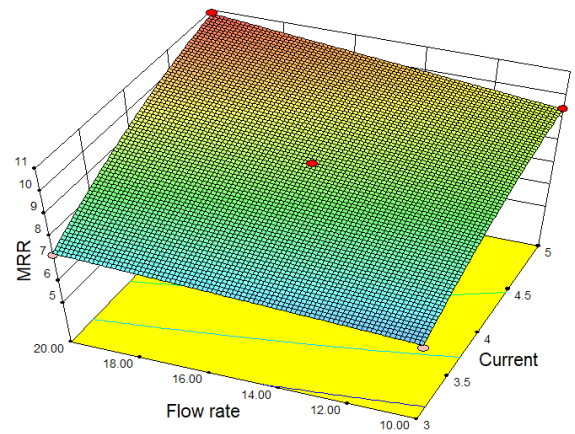by reducing pulse-interval due to an increase in spark ideal time.

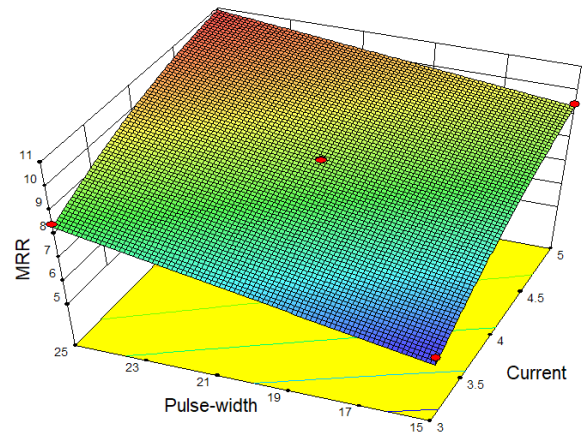**Fig. 2.** *Response surface for MRR concerning flow rate and current*

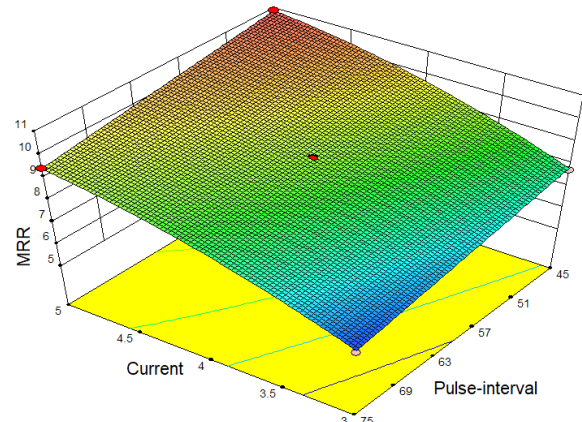**Fig. 3.** *Response surface for MRR concerning pulse-width and current*

Fig. 4. *Response surface for MRR concerning current and pulse-interval*

Table 3. *Lack of fit test for material removal rate model*

Source	Sum of squares	Degree of freedom	Mean sum square	F-value	p-value $> F$	Comments
Linear	2.040	20	0.102	4.383	0.081	Insignificant
2FI	1.513	14	0.108	4.644	0.075	Insignificant
Quadratic	0.215	10	0.022	0.924	0.584	Suggested
Cubic	0.036	2	0.018	0.775	0.520	Aliased
Pure Error	0.093	4	0.023	-	-	-

Table 4. *Data analysis of material removal rate*

Source	Sum of squares	Degree of freedom	Mean square	F-value	p-value $> F$	Remarks	Contribution [%]
Model	54.491	8	6.811	404.036	< 0.0001	Significant	99.39
Current (C)	29.016	1	29.016	1721.184	< 0.0001	Significant	52.92
Pulse-width (PW)	13.504	1	13.504	801.052	< 0.0001	Significant	24.63
Pulse-interval (PI)	7.023	1	7.023	416.571	< 0.0001	Significant	12.81
Flow rate(F)	3.152	1	3.152	186.962	< 0.0001	Significant	5.75
$C \times PW$	0.354	1	0.354	21.000	0.0002	Significant	0.65
$C \times PI$	0.011	1	0.011	0.654	0.4282*	Not significant	0.02
$C \times F$	0.160	1	0.160	9.491	0.0059	Significant	0.29
C^2	1.271	1	1.271	75.369	< 0.0001	Significant	2.32
Residual	0.337	20	0.017	-	-	-	-
Lack of fit	0.244	16	0.015	0.656	0.7580	Not significant	-
Pure error	0.093	4	0.023	-	-	-	-
Cor total	54.8281	28	-	-	-	-	-

Table 5. *Lack of fit test for WWR model*

Source	Sum of squares	Degree of freedom	Mean square	F-value	p-value $> F$	Comments
Linear	0.06	20.00	0.00	4.78	0.070	Insignificant
2FI	0.01	14.00	0.00	0.92	0.601	Insignificant
Quadratic	0.00	10.00	0.00	0.11	0.998	Suggested
Cubic	0.00	2.00	0.00	0.08	0.927	Aliased
Pure Error	0.00	4.00	0.00	-	-	-

Table 6. *Data analysis of wire wear ratio*

Source	Sum of squares	Degree of freedom	Mean square	F-value	p-value $> F$	Remarks	Contribution [%]
Model	0.7747	8.0000	0.0968	411.8384	< 0.0001	Significant	99.40
Current (C)	0.1160	1.0000	0.1160	493.4670	< 0.0001	Significant	14.89
Pulse-width (PW)	0.0760	1.0000	0.0760	323.2220	< 0.0001	Significant	9.75
Pulse-interval (PI)	0.4848	1.0000	0.4848	2061.8105	< 0.0001	Significant	62.20
Flow rate(F)	0.0424	1.0000	0.0424	180.1662	< 0.0001	Significant	5.44
$C \times PW$	0.0406	1.0000	0.0406	172.6734	< 0.0001	Significant	5.21
$PW \times PI$	0.0077	1.0000	0.0077	32.9337	< 0.0001	Significant	0.99
$PI \times F$	0.0012	1.0000	0.0012	4.9162	0.0384	Significant	0.15
PI^2	0.0060	1.0000	0.0060	25.5181	< 0.0001	Significant	0.77
Residual	0.0047	20.0000	0.0002			-	0.60
Lack of fit	0.0023	16.0000	0.0001	0.2360	0.9842	Not significant	-
Pure error	0.0024	4.0000	0.0006	-	-	-	-
Cor total	0.7794	28.0000	-	-	-	-	-

The minimization of *WWR* is one of the goals of this study. The *WWR* 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 Fig. 5. While

the increase in pulse-width, the spark strength is significantly increased with material removal rate and reduced the *WWR*. The increase in pulse-interval is increasing the *WWR* due to the high spark pause time [5]. Fig. 6 shows the interaction effects of pulse-width and current on *WWR*. While increasing the spark current, the *WWR* value is exploiting due to heave spark intensity [20] and [21]. Similarly, the *WWR* value is also slowly increased due to the growing *MRR* by fast flushing debris, as shown in Fig. 7.
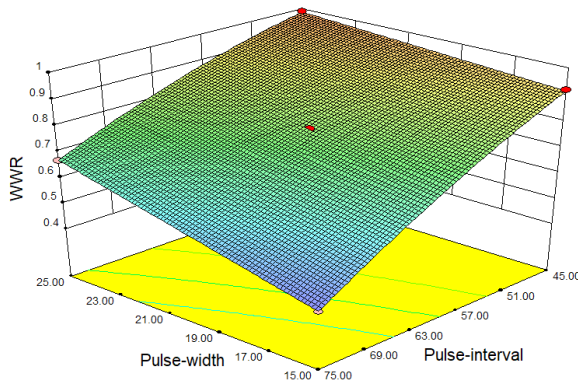
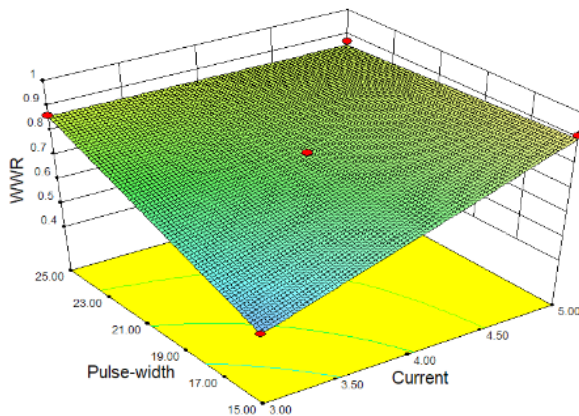**Fig. 5.** *Response surface for WWR concerning pulse-width and pulse-interval*

Fig. 6. *Response surface for WWR concerning pulse-width and current*

The wire wear ratio has been analysed with scanning electron microscopy (SEM) photograph, as shown in Fig. 8. It was observed that the wear on the wire is linearly along the axis due to the reciprocating wire longitudinally. The crater of materials in the wire is high at the point 'P' due to the sudden supply of current to the wire. The path 'QR' is sparking a portion of the wire, which is in direct with the workpiece. The high temperature along the 'QR' path due to frequent changes of power supply between the wire and workpiece causes to increase the wear ratio.

The path 'ST' is a non-spark portion of the wire tool, which has the minimum crater of wear.
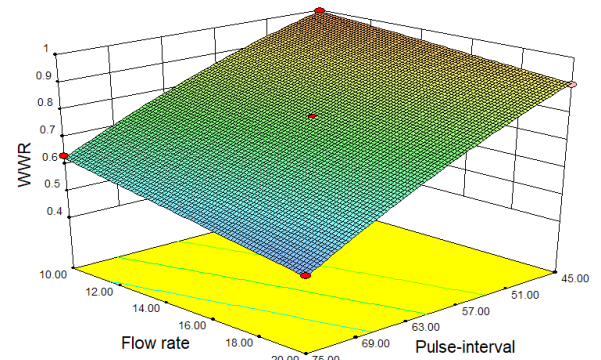

Fig. 7. *Response surface for WWR concerning flow rate and pulse-interval*
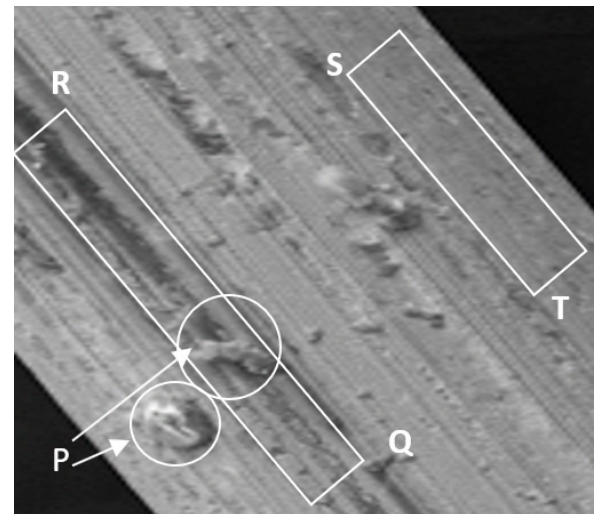

Fig. 8. *SEM photograph of wire electrode wear*

3 MULTI-OBJECTIVE OPTIMIZATION AND VALIDATION OF PREDICTION

In this stage, the combination of experimental parameters and their response based on the standard ranges defined for the responses are predicted [22]. Based on the desirability function, techniques were used to predict the best results of both responses. This process detects a point that improves the desirability function [23]. For validating the developed models, some solutions were selected randomly. The optimized predicted values of the output responses were compared to experimentally obtained values [24]. The combination of variables that presents the overall optimum desirability (99 %) of response and contour plots is displayed in Fig. 8. Considering all the quality attributes and using the optimization method with

Table 7. *Predicted Results from desirability and validation by confirmation experiments*

No	C [A]	PW [µs]	PI [µs]	F [ml/min]	MRR [mm³/min]	WWR	Description
1	5	25	75	20	10.91	0.59	Desirability Approach
2	5	25	75	20	11.00	0.62	Near-dry WEDM
3	5	25	75	2 litres/min	17.42	0.83	Conventional WEDM

which the quality parameters were put into standard ranges (*MRR* and *WWR*), formulation one consisting of 25 µs pulse-width, 75 µs pulse-interval, 5 A current, and 20 ml/min flow rate was selected as having the maximum desirability. The combined optimizing responses are predicted as 10.91 mm³/min of material removal rate, and 0.59 of *WWR*.

Confirmation tests were conducted to validate the predicted optimum process parameters for best *MRR* and *WWR*, as shown in Table 7. The multi-optimization results were confirmed by the mean observed values of the test. The 5 A current, pulse-width 25 µs, pulse-interval 75 µs, and 20 ml/min flow rate gives 11 mm³/min of *MRR* and 0.62 % of *WWR*.

The desirability principles were applied to obtain the multi-objective solutions to optimize both responses. It is very useful for machine operators to select the best process parameters for minimum *WWR* and maximum *MRR*. These results are used by WEDM machine manufacturers to fix the best (default) setting for cryogenically cooled oxygen-mist near-dry wire-cut electrical discharge machining (NDWEDM) process.
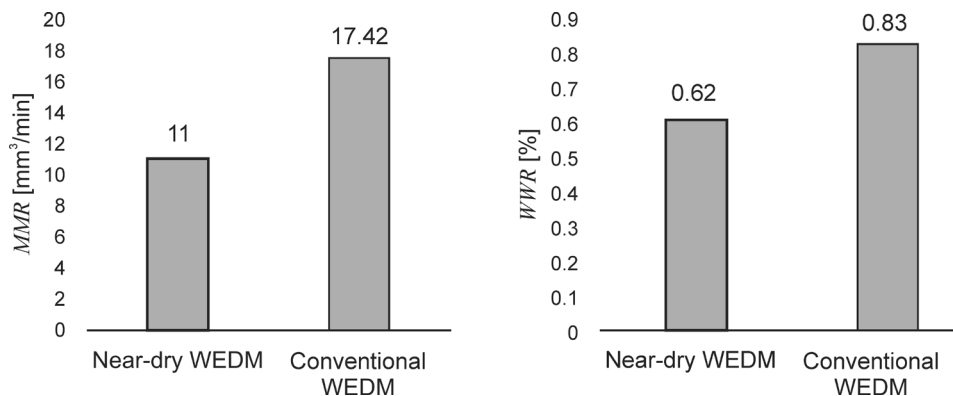
4 COMPARISON OF CRYOGENICALLY COOLED NEAR-DRY AND CONVENTIONAL WEDM

The predicted best combinations of input parameters were considered for the comparative analysis. In Fig. 9, the *MRR* and *WWR* of cryogenically cooled near-dry WEDM are compared with the conventional process. The range of input parameters of both processes are

current 5 A, pulse-width 25 µs, and pulse-interval 75 µs. The flow rate of oxygen-mist of near-dry WEDM is 20 ml/min, and the water flow rate of conventional WEDM is 2 l/min. As per the literature, the near-dry WEDM is an effective eco-friendly process while comparing with conventional WEDM [4], [13] to [15]. The *MRR* of the near-dry WEDM process was comparatively lower than the conventional process due to the significant flush out of removed material from the workpiece. The *WWR* of the near-dry process is lower than conventional WEDM because the heat dissipation from the wire is improved by increasing the thermal conductivity of the cryogenic cooling wire [16]. The minimum *WWR* promotes the life of reusable wire electrode.

5 CONCLUSIONS

In this research, data were collected from the experiments of oxygen-mist cryo-cooled wire near-dry WEDM were carried out to maintain enough temperature in the cutting zone to cut the Inconel 718 alloy material. The electrical conductivity of cryogenically cooled molybdenum wire was significantly increased in the near-dry WEDM process. It was observed that pulse-width, pulse-interval, current, and flow rate are significant parameters on the material removal rate and wire wear ratio. The current and pulse-width are the most important factors for material removal rate. Increasing the current and pulse-width, the material removal rate

Fig. 9. *Comparisons of machining performances between cryogenically cooled near-dry and conventional WEDM*

was increasing and same time decreasing the WWR. While increasing pulse-interval from 45 µs to 75 µs, both the material removal rate and WWR were decreased. The WWR has been significantly reduced at the dielectric fluid flow rate of 20 ml/min. It was observed from the SEM photograph that the wire wear rate is linear to the axis, and the wear rate is high along the spark path of the wire tool. Thus, the optimum process parameters were obtained for the cryo-cooled molybdenum wire electrode used in the oxygen-mist near-dry wire-cut electrical discharge machining process. The desirability technique was used to find the best solution among the conflict behaviour of *MRR* and *WWR*. It was observed that the behaviour of the parameters against response variables is the same as with the response surface method. The current 5 A, pulse-width 25 µs, pulse-interval 75 µs, and 1 ml/min flow rate give 10.97 mm^3/min of *MRR* and 0.59 of *WWR*. The multi-optimization results were validated by the mean observation value of confirmation experiments. These results are used by manufacturers and operators to fix the best (default) setting for the cryogenically cooled oxygen-mist NDWEDM process.

In near-dry WEDM, the cryogenically cooling of wire significantly contributed to reducing *WWR* than to *MRR*. While comparing conventional WEDM, the *WWR* of near-dry WEDM was very lower. The lowest *WWR* increases the life of reusable molybdenum wire tools. As per the literature, the near-dry WEDM is an effective eco-friendly process while comparing with conventional WEDM. However, the *MRR* of near-dry WEDM is lower than that of the conventional WEDM process.

6 ACKNOWLEDGEMENTS

7 NOMENCLATURES

PW	pulse-width, [µs]
PI	pulse-interval, [µs]
C	spark current, [A]
F	flowrate, [ml/s]
MRR	material removal rate [mm^3/min]
WWR	wire wear ratio [-]
f(*x*)	Function of '*x*'
$x_1, x_2, …, x_n$	independent variables
$\beta_0, \beta_i, \beta_{ij}$	model coefficients

ϕ	statistical error
R^2	coefficient of determination
FI	factor interaction
F-value	Values from statistical "*F*" table

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