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A simple and reliable Taguchi approach for multi-objective optimization to identify optimal process parameters in nano-powder-mixed electrical discharge machining of INCONEL800 with copper electrode

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ABSTRACT

There is a need for heavy-duty machining equipment and tooling to minimize chatter due to work-hardening of the INCONEL materials ahead of cutting. Optimum EDM parameters are to be identified to produce quality products of INCONEL800. Modified Taguchi approach is adopted in the multi-objective optimization to identify the optimum peak current, pulse-on-time and pulse-off-time in the nano powder mixed EDM (n-PMEDM) of INCONEL800 with copper electrode for high material removal rate (MRR) and low surface roughness (SR). Empirical relations for MRR and SR are developed easily in terms of the EDM parameters without use of the MINITAB Release-16 software and validated with test results. Test results are found to be within the expected range. It also demonstrates the advantages of opting Taguchi approach to get complete information through few experiments.

1. Introduction

Electrical discharge machining (EDM) is a thermo-electric process involving the formation of a plasma channel between the tool and the work-piece. Such a process is useful in the machining of super-tough electrically conductive materials. INCONEL800 is an iron nickel chromium alloy having moderate strength, good resistance to corrosion and carburization at elevated temperatures being used in nuclear reactors, chemical vessels, electrical power plant equipment and equipment in petrochemical industry. Die sinking EDM and wire cut EDM (WEDM) are two types of EDM processes. Both electrode and work-piece are immersed in insulating fluid (dielectric) in die sinking EDM. In WEDM a thin single-strand metal wire (usually brass) in contact with de-ionised water allows the wire to cut through metal by the use of heat from electrical sparks. Other types of EDM include vibrorotary based EDM (VRVEDM), water EDM, dry EDM and powder mixed EDM (PMEDM). In vibrorotary EDM the tool is given a vibration in the longitudinal axis while both the work-piece and the tool can be provided a rotary motion. In water EDM the dielectric fluid is replaced with water, whereas a suitable gas is used in dry EDM. In PMEDM the dielectric is mixed with different metallic powders to minimize arcing problem. Vibrorotary based EDM mechanism provides better circulation of fluid and removal of debris leading to an increased MRR and surface finish. Both water EDM and dry EDM processes provide high MRR and surface finish controlling hazardous fumes. PMEDM process provides high MRR, increases conductive strength, spark gap distance and mirror like surface finish without burrs and machining stresses [1].

Extensive experimental work has been carried out to identify the optimum machining parameters for INCONEL materials using EDM [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12], WEDM [13, 14, 15, 16], VRVEDM [17, 18, 19], Water in EDM [20], Dry EDM [21, 22, 23, 24, 25] and PMEDM [26, 27, 28, 29, 30]. Most of these researchers have utilized the concept of design of experiments. Taguchi has devised a standard method for analysing the test results by defining a set of orthogonal array [31, 32, 33, 34, 35, 36, 37, 38, 39]. This method demands few experiments and provides information of the full factorial design of experiments. Many of these researchers have applied the signal-to-noise (S/N) ratio transformation on a single value of output response in each test run and performed the analysis of variance (ANOVA). Some have employed Grey-Taguchi method and genetic algorithms to optimize the process with multiple objectives and adjusted the process parameters to achieve high MRR and surface finish. In fact, Taguchi has recommended S/N ratio transformation to accommodate several repetitions into a single value which reflects the scatter in the test data. Hence, S/N ratio transformation concept created by many researchers on a single value output response to each test run has no benefit other than additional computing tasks [34,

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36]. It is also observed that many methods are adopted without demonstrating the drawbacks in the widely used simple Taguchi approach. In general, the optimal process parameters are different for each output response. An appropriate multi-objective optimization technique is required for tracing a set of optimal process parameters [31, 32, 33, 34, 35, 36, 37, 38].

Karunakaran and Chandrashekaran [30] have examined the influence of process parameters in PMEDM adopting the Taguchi full factorial design derived from MINITAB Release-16 software with three input parameters each having three levels. They have found different optimal machining conditions for high MRR and low SR. However, optimum EDM parameters can be easily found using Taguchi's design of experiments considering L_9 orthogonal arrays. The objective of this paper is to present optimum machining parameters of nano powder mixed EDM (n-PMDEM) of INCONEL800 using a simple and reliable multi-objective optimization technique involving weighing factors following the Taguchi approach. It also demonstrates the adequacy of Taguchi approach by considering few experimental data and generating the output responses for the full factorial deign and validating with test data.

2. Analysis

To examine the influence of process parameters in n-PMEDM of INCONEL800 with copper electrode, Karunakaran and Chandrsekharan [30] have conducted experiments employing the die sinking CNC EDM machine (Xpert1 model of Electronica India Limited). Use of the low viscosity kerosene as dielectric fluid gets flushed away easily. Aluminum powder is mixed with kerosene and stirred in the magnetic stirrer for nearly nine hours to minimize the size of particles to 5 Nm. Aluminum nano powder concentration is 3 g/l. The n-PMEDM minimizes arcing problems. In the design of experiments gap current, pulse-on-time and pulse-off-time are three independent process variables to examine their influence on the material removal rate (MRR) and the surface roughness (SR). The INCONEL800 work-piece and electrolytic copper tool material are of the size $\phi 22 \times 20\ \ mm$ and $\phi 25 \times 23\ \ mm$ respectively. Machining time in each test run is set for 5 minutes. The high sensitivity semi-micro analytical balance (having a minimum reading capability of 10^{-5} grams) is used to measure the weight losses of the tool and the work-piece. The material removal rate, $MRR = \frac{W_1 - W_2}{t}$, is evaluated using the weights of the sample before and after machining (W_1 and W_2) and the machining time (t). The Taylor-Hobson Surtronic 3 roughness gage (a contact-type surface roughness measuring system) is used for assessing the roughness (from the average of three readings) with 0.8mm cut of length. The full factorial design from MINITAB Release-16 software in [30] demands 27 experiments with three input EDM parameters (viz., gap current, pulse-on-time and pulse-off-time) each having three levels, and found different optimal machining conditions for high MRR and low SR. It is possible to find optimal EDM parameters from 9 experiments using Taguchi's L_9 orthogonal arrays. The test data [30] is very much useful to demonstrate the adequacy of Taguchi approach for obtaining the required information through few experiments.

Many factors or process parameters influence the outcome of the experiments. It is possible through design of experiments to carry out experiments in a systematic way and assess individual contributions of process parameters and their intricate relationship. Reliable empirical relations can be developed for the output responses in terms of input variables. Multi-objective optimization can provide a set of optimal process parameters. It is possible to provide the expected range for the output responses to the specific process parameters.

Current design of experiments involves gap current, pulse-on-time and pulse-off-time as the independent process variables; levels for each process variable; appropriate orthogonal array to assign process variable to respective column of orthogonal array; performing experiments for measuring MRR and SR as the output responses. Table 1 gives the levels of process parameters and the output responses (viz., MRR and SR) as per Taguchi's L_9 orthogonal array. ANOVA is done for the optimum process parameters to obtain maximum MRR and minimum SR. The process parameters viz., peak current, pulse-on-time and pulse-off-time are designated by A, B and C respectively.

Table 1
Levels of process parameters and the output responses as per L_9 orthogonal array.

Assignment levels of process parameters n-PMEDM of INCONEL800 with copper electrode				
Input parameters	Designated Factor	Level -1	Level-2	Level-3
Peak Current (Amp)	A	5	10	15
Pulse- on-time (µs)	B	6	7	8
Pulse-off-time (µs)	C	3	4	5

Output responses							
Test Run	Levels of input parameters			Output responses			
				MRR (g/min)		SR (µm)	
	A	B	C	Test [30]	Estimate Eq. (1)	Test [30]	Estimate Eq. (1)
1	1	1	1	0.11438	0.1216	0.98	0.9433
2	1	2	2	0.31560	0.295	1.18	1.18
3	1	3	3	0.55829	0.5723	1.33	1.3666
4	2	1	2	0.22548	0.2392	1.21	1.2466
5	2	2	3	0.43447	0.4414	1.49	1.4533
6	2	3	1	0.60079	0.581	1.27	1.27
7	3	1	3	0.46089	0.4409	1.54	1.5399
8	3	2	1	0.49270	0.5054	1.34	1.3767
9	3	3	2	0.74722	0.7539	1.63	1.5933

Table 2
ANOVA for MRR and SR.

Input parameters	1-Mean	2-Mean	3-Mean	Sum of squares	% contribution
Material removal rate (MRR)					
A	0.3296	0.4205	**0.5667**	0.0859	28.2
B	0.2672	0.4139	**0.6357**	0.2065	67.7
C	0.4026	0.4293	**0.4848**	0.0106	3.5
Surface roughness (SR)					
A	1.1633	1.3233	**1.5033**	0.1736	53.8
B	1.2433	1.3367	**1.4100**	0.0419	13.0
C	1.1967	1.3400	**1.4533**	0.0993	30.8

Let ψ_i ($i = 1\ \ to\ \ 9$) be the one of the output responses (viz., the material removal rate, MRR) of the i^{th} test run in Table 1 of the Taguchi's L_9 orthogonal array. The mean value of ψ for the 9 test runs, $\psi_{mean} = (\sum_{i=1}^{9}\psi_i)/9 = 0.4389$ g/min and the total sum of squares, $\psi_{SOS\ (T)} = \sum_{i=1}^{9}(\psi_i - \psi_{mean})^2 = 0.3048$. The mean values of ψ are designated by $\overline{\psi}_{Ai}$, $\overline{\psi}_{Bi}$ and $\overline{\psi}_{Ci}$ ($i = 1$ *to* 3) for i^{th} level of A, B and C process parameters. The evaluation process in ANOVA analysis results of Table 2 for the MRR is as follows.

1-Mean values of MRR for the level-1 of A, B, and C are: $\overline{\psi}_{A1} = (\psi_1 + \psi_2 + \psi_3)/3 = 0.3296$; $\overline{\psi}_{B1} = (\psi_1 + \psi_4 + \psi_7)/3 = 0.2672$; and $\overline{\psi}_{C1} = (\psi_1 + \psi_6 + \psi_8)/3 = 0.4026$, respectively.

2-Mean values of MRR for the level-2 of A, B and C are: $\overline{\psi}_{A2} = (\psi_4 + \psi_5 + \psi_6)/3 = 0.4205$; $\overline{\psi}_{B2} = (\psi_2 + \psi_5 + \psi_8)/3 = 0.4139$; and $\overline{\psi}_{C2} = (\psi_2 + \psi_4 + \psi_9)/3 = 0.4293$, respectively.

3-Mean values of MRR for the level-3 of A, B and C are: $\overline{\psi}_{A3} = (\psi_7 + \psi_8 + \psi_9)/3 = 0.5667$; $\overline{\psi}_{B3} = (\psi_3 + \psi_6 + \psi_9)/3 = 0.6357$; and $\overline{\psi}_{C3} = (\psi_3 + \psi_5 + \psi_7)/3 = 0.4848$, respectively.

Denoting the differential responses $\Delta\overline{\psi}_{Ai}$, $\Delta\ \overline{\psi}_{Bi}$ and $\Delta\overline{\psi}_{Ci}$ ($i = 1$ *to* 3) to the i^{th} level of A, B and C and evaluating the sum of squares of deviation from the mean for A, B and C for MRR are:

$\psi_{SOS\ (A)} = 3\sum_{i=1}^{3}(\Delta\overline{\psi}_{Ai})^2 = 3\sum_{i=1}^{3}(\overline{\psi}_{Ai} - \psi_{mean})^2 = 0.0859$;

$\psi_{SOS\ (B)} = 3\sum_{i=1}^{3}(\Delta\overline{\psi}_{Bi})^2 = 3\sum_{i=1}^{3}(\overline{\psi}_{Bi} - \psi_{mean})^2 = 0.2065$; and

$\psi_{SOS\ (C)} = 3\sum_{i=1}^{3}(\Delta\overline{\psi}_{Ci})^2 = 3\sum_{i=1}^{3}(\overline{\psi}_{Ci} - \psi_{mean})^2 = 0.0106$.

%Contribution of A, B and C to the total variation obtained for MRR are:

$\%C_A = 100 \times \frac{\psi_{SOS\,(A)}}{\psi_{SOS\,(T)}} = 28.2$;

$\%C_B = 100 \times \frac{\psi_{SOS\,(B)}}{\psi_{SOS\,(T)}} = 67.7$; and

$\%C_C = 100 \times \frac{\psi_{SOS\,(C)}}{\psi_{SOS\,(T)}} = 3.5$.

$Error\ (\%) = 100 - (\%C_A + \%C_B + \%C_C) = 100 - (28.2 + 67.7 + 3.5) = 0.6$

The other output response (viz., the surface roughness, SR) is assumed as φ_i ($i = 1$ *to* 9) for the i^{th} test run in Table 1 of the Taguchi's L_9 orthogonal array. The mean value of φ for the 9 test runs, $\varphi_{mean} = (\sum_{i=1}^{9}\varphi_i)/9 = 1.33\ \mu m$ and the total sum of squares, $\phi_{SOS\,(T)} = \sum_{i=1}^{9}(\varphi_i - \varphi_{mean})^2 = 0.3228$. The mean values of φ are designated by $\overline{\varphi}_{Ai}$, $\overline{\varphi}_{Bi}$ and $\overline{\varphi}_{Cl}$ ($i = 1$ *to* 3) for i^{th} level of A, B and C process parameters. The evaluation process in ANOVA analysis results of Table 2 for the SR is as follows.

1-Mean values of SR for the level-1 of A, B, and C are: $\overline{\varphi}_{A1} = (\varphi_1 + \varphi_2 + \varphi_3)/3 = 1.1633$; $\overline{\varphi}_{B1} = (\varphi_1 + \varphi_4 + \varphi_7)/3 = 1.2433$; and $\overline{\varphi}_{C1} = (\varphi_1 + \varphi_6 + \varphi_8)/3 = 1.1967$, respectively.

2-Mean values of SR for the level-2 of A, B and C are: $\overline{\varphi}_{A2} = (\varphi_4 + \varphi_5 + \varphi_6)/3 = 1.3233$; $\overline{\varphi}_{B2} = (\varphi_2 + \varphi_5 + \varphi_8)/3 = 1.3367$; and $\overline{\varphi}_{C2} = (\varphi_2 + \varphi_4 + \varphi_9)/3 = 1.34$, respectively.

3-Mean values of SR for the level-3 of A, B and C are: $\overline{\varphi}_{A3} = (\varphi_7 + \varphi_8 + \varphi_9)/3 = 1.5033$; $\overline{\varphi}_{B3} = (\varphi_3 + \varphi_6 + \varphi_9)/3 = 1.41$; and $\overline{\varphi}_{C3} = (\varphi_3 + \varphi_5 + \varphi_7)/3 = 1.4533$, respectively.

Denoting the differential responses $\Delta\overline{\varphi}_{Ai}$, $\Delta\,\overline{\varphi}_{Bi}$ and $\Delta\overline{\varphi}_{Ci}$ ($i = 1$ *to* 3) to the i^{th} level of A, B and C and evaluating the sum of squares of deviation from the mean for A, B and C for SR are:

$\varphi_{SOS\,(A)} = 3\sum_{i=1}^{3}(\Delta\overline{\varphi}_{Ai})^2 = 3\sum_{i=1}^{3}(\overline{\varphi}_{Ai} - \varphi_{mean})^2 = 0.1736$;

$\varphi_{SOS\,(B)} = 3\sum_{i=1}^{3}(\Delta\overline{\varphi}_{Bi})^2 = 3\sum_{i=1}^{3}(\overline{\varphi}_{Bi} - \varphi_{mean})^2 = 0.0419$; and

$\varphi_{SOS\,(C)} = 3\sum_{i=1}^{3}(\Delta\overline{\varphi}_{Ci})^2 = 3\sum_{i=1}^{3}(\overline{\varphi}_{Ci} - \varphi_{mean})^2 = 0.0993$.

%Contribution of A, B and C to the total variation for SR obtained are:

$\%C_A = 100 \times \frac{\varphi_{SOS\,(A)}}{\varphi_{SOS\,(T)}} = 53.8$;

$\%C_B = 100 \times \frac{\varphi_{SOS\,(B)}}{\varphi_{SOS\,(T)}} = 13.0$; and

$\%C_C = 100 \times \frac{\varphi_{SOS\,(C)}}{\varphi_{SOS\,(T)}} = 30.8$.

$Error\ (\%) = 100 - (\%C_A + \%C_B + \%C_C) = 100 - (53.8 + 13.0 + 30.8) = 2.4$

The ANOVA results of Table 2 indicate the influence of process parameters on MRR as pulse-on-time with 67.7 % contribution, peak current with 28.2 % contribution and pulse-off-time with 3.5 % contributions. Peak current has 53.8 % contribution on SR, whereas the pulse-on-time and pulse-off-time have 13.0 %, and 30.5 % contributions.

ANOVA has been performed for the EDM process to estimate MRR and SR for the assigned levels of machining parameters for each test run using the additive law [39]. In the additive law [39], the output response, ϕ can be estimated utilizing its mean values for the specified levels of the input process parameter $(X_1^l, X_2^l, \ldots, X_{n_p}^l)$ from

$$\widehat{\phi} = \phi\left(X_1^l,\ X_2^l, \ldots, X_{n_p}^l\right) = \phi_{mean} + \sum_{j=1}^{n_p}\left(\phi_{Xj}^l - \phi_{mean}\right) = \sum_{j=1}^{n_p}\phi_{Xj}^l - \left(n_p - 1\right)\phi_{mean} \tag{1}$$

Here $\widehat{\phi}$ is the estimate of ϕ for the specified levels of the input process parameter $(X_1^l, X_2^l, \ldots, X_{n_p}^l)$; ϕ_{mean} is the gross mean of ϕ for total test runs; ϕ_{Xj}^l is the mean value of ϕ for the desired level (l) of the input process parameter, X_j^l; and n_p is the number of input process parameters.

From ANOVA Table 2, the process parameters for the maximum MRR are $A_3B_3C_3$, in which subscripts denote the level. The process parameters for minimum SR are $A_1B_1C_1$. Confirmation experiments are mandatory.

For the identified process parameters (A_3, B_3, C_3), the maximum value of MRR estimated from Eq. (1) as follows. The number of process parameters, $n_p = 3$; $A_3 = X_1^3 = 15$ Amp; $B_3 = X_2^3 = 8\ \mu s$; and $C_3 = X_3^3 = 5\ \mu s$. From ANOVA Table 2, the mean values of the output response, ϕ (MRR in the present case) corresponding to the above levels of the process parameters are: $\phi_{X1}^3 = 0.5667$ g/min; $\phi_{X2}^3 = 0.6357$ g/min; $\phi_{X3}^3 = 0.4848$ g/min; $\phi_{mean} = 0.4389$ g/min. The maximum value of MRR obtained from Eq. (1) using the above data as: $(MRR)_{\max} = \widehat{\phi}_{\max} = \phi(X_1^3 = A_3,\ X_2^3 = B_3,\ X_3^3 = C_3) = \phi_{X1}^3 + \phi_{X2}^3 + \phi_{X3}^3 - 2 \times \phi_{mean} = 0.5667 + 0.6357 + 0.4848 - 2 \times 0.4389 = 0.8094$ g/min.

Similarly for the identified process parameters(A_1, B_1, C_1), the minimum value of SR estimated from Eq. (1) as follows. The number of input process parameters, $n_p = 3$; $A_1 = X_1^1 = 5$ Amp; $B_1 = X_2^1 = 6\ \mu s$; and $C_1 = X_3^1 = 3\ \mu s$. From ANOVA Table 2, the mean values of the output response, ϕ(SR in the present case) corresponding to the above levels of the process parameters are:$\phi_{X1}^1 = 1.1633\ \mu m$; $\phi_{X2}^1 = 1.2433\ \mu m$; $\phi_{X3}^1 = 1.1967\ \mu m$; and $\phi_{mean} = 1.33\ \mu m$. The minimum value of SR obtained from Eq. (1) using the above data as: $(SR)_{\min} = \widehat{\phi}_{\min} = \phi(X_1^1 = A_1,\ X_2^1 = B_1,\ X_3^1 = C_1) = \phi_{X1}^1 + \phi_{X2}^1 + \phi_{X3}^1 - 2 \times \phi_{mean} = 1.1633 + 1.2433 + 1.1967 - 2 \times 1.33 = 0.9433 \mu m$.

For the above identified process parameters, the optimum values of MRR and SR from Eq. (1) are 0.8094 g/min and 0.9433 μm respectively, whereas the test results are 0.79346 g/min and 0.98 μm respectively.

Empirical relations for MRR and SR in terms of peak current (A), pulse-on-time (B) and pulse-off-time (C) from the mean values in Table 2 using the additive law developed are

$$MRR = (MRR)_A + (MRR)_B + (MRR)_C - 2 \times (MRR)_{mean} = 0.001106A^2 + 0.03755B^2 + 0.0144C^2 + 0.00159A - 0.34145B - 0.0741C + 0.8756 \tag{2}$$

$$SR = (SR)_A + (SR)_B + (SR)_C - 2 \times (SR)_{mean} = 0.0004A^2 - 0.01005B^2 - 0.015C^2 + 0.026A + 0.22405B + 0.2483C - 0.7891 \tag{3}$$

Considering the three mean values of the output responses (MRR andSR) corresponding to the three level values of the input process parameters (A, B and$C$), one can express the relations in quadratic form as

$$(MRR)_A = \Psi_{12}A^2 + \Psi_{11}A + \Psi_{10} = 0.001106A^2 + 0.00159A + 0.294 \tag{4}$$

Here $\Psi_{10} = \overline{\psi}_{A1} - \Psi_{11}A_1 - \Psi_{12}A_1^2$; $\Psi_{11} = \frac{(\overline{\psi}_{A1} - \overline{\psi}_{A2})}{(A_1 - A_2)} - \Psi_{12}(A_1 + A_2)$; and $\Psi_{12} = \frac{1}{A_1 - A_2}\left\{\frac{\overline{\psi}_{A1} - \overline{\psi}_{A2}}{A_1 - A_2} - \frac{\overline{\psi}_{A2} - \overline{\psi}_{A3}}{A_2 - A_3}\right\}$.

$$(MRR)_B = \Psi_{22}B^2 + \Psi_{21}B + \Psi_{20} = 0.03755B^2 - 0.34145B + 0.9641 \tag{5}$$

Here $\Psi_{20} = \overline{\psi}_{B1} - \Psi_{21}B_1 - \Psi_{22}B_1^2$; $\Psi_{21} = \frac{\overline{\psi}_{B1} - \overline{\psi}_{B2}}{B_1 - B_2} - \Psi_{22}(B_1 + B_2)$; and $\Psi_{22} = \frac{1}{B_1 - B_2}\left\{\frac{\overline{\psi}_{B1} - \overline{\psi}_{B2}}{B_1 - B_2} - \frac{\overline{\psi}_{B2} - \overline{\psi}_{B3}}{B_2 - B_3}\right\}$.

$$(MRR)_C = \Psi_{32}C^2 + \Psi_{31}C + \Psi_{30} = 0.0144C^2 - 0.0741C + 0.4953 \tag{6}$$

Here $\Psi_{30} = \overline{\psi}_{C1} - \Psi_{31}C_1 - \Psi_{32}C_1^2$; $\Psi_{31} = \frac{\overline{\psi}_{C1} - \overline{\psi}_{C2}}{C_1 - C_2} - \Psi_{32}(C_1 + C_2)$; and $\Psi_{32} = \frac{1}{C_1 - C_2}\left\{\frac{\overline{\psi}_{C1} - \overline{\psi}_{C2}}{C_1 - C_2} - \frac{\overline{\psi}_{C2} - \overline{\psi}_{C3}}{C_2 - C_3}\right\}$.

$$(SR)_A = \Phi_{12}A^2 + \Phi_{11}A + \Phi_{10} = 0.0004A^2 + 0.026A + 1.0233 \tag{7}$$

Here$\Phi_{10} = \overline{\varphi}_{A1} - \Phi_{11}A_1 - \Phi_{12}A_1^2$; $\Phi_{11} = \frac{(\overline{\varphi}_{A1} - \overline{\varphi}_{A2})}{(A_1 - A_2)} - \Phi_{12}(A_1 + A_2)$; and $\Phi_{12} = \frac{1}{A_1 - A_2}\left\{\frac{\overline{\varphi}_{A1} - \overline{\varphi}_{A2}}{A_1 - A_2} - \frac{\overline{\varphi}_{A2} - \overline{\varphi}_{A3}}{A_2 - A_3}\right\}$.

$$(SR)_B = \Phi_{22}B^2 + \Phi_{21}B + \Phi_{20} = -0.01005B^2 + 0.22405B + 0.2608 \tag{8}$$

Here$\Phi_{20} = \overline{\varphi}_{B1} - \Phi_{21}B_1 - \Phi_{22}B_1^2$; $\Phi_{21} = \frac{\overline{\varphi}_{B1} - \overline{\varphi}_{B2}}{B_1 - B_2} - \Phi_{22}(B_1 + B_2)$; and

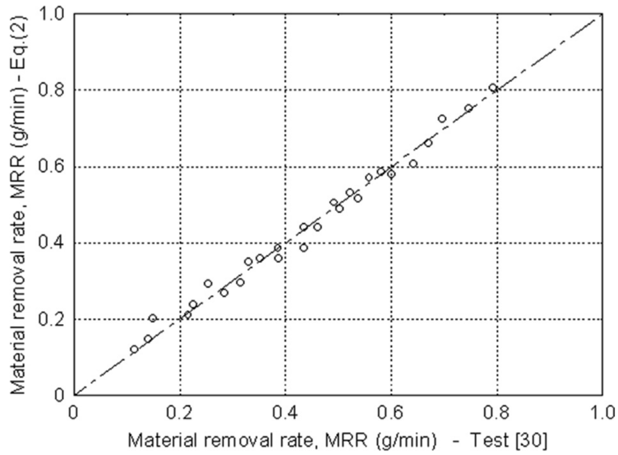

Fig. 1. Comparison of estimates of the material removal rate (MRR) with test results [30].

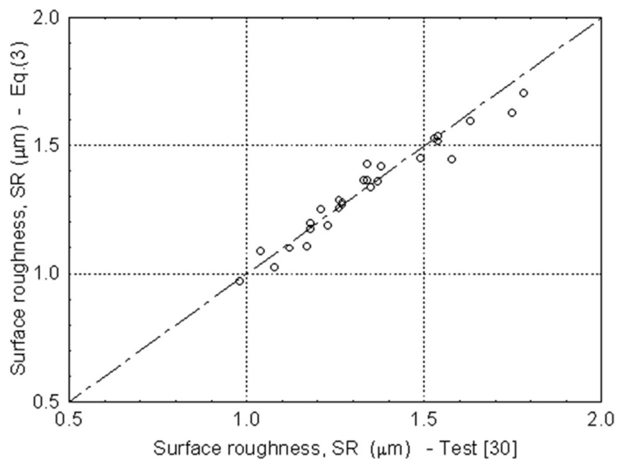

Fig. 2. Comparison of estimates of surface roughness (SR) with test results [30].

$$\Phi_{22} = \frac{1}{B_1-B_2}\left\{\frac{\overline{\varphi}_{B1}-\overline{\varphi}_{B2}}{B_1-B_2} - \frac{\overline{\varphi}_{B2}-\overline{\varphi}_{B3}}{B_2-B_3}\right\}.$$

$$(SR)_C = \Phi_{32}C^2 + \Phi_{31}C + \Phi_{30} = -0.015C^2 + 0.2483C + 0.5868 \tag{9}$$

Here $\Phi_{30} = \overline{\varphi}_{C1} - \Phi_{31}C_1 - \Phi_{32}C_1^2$; $\Phi_{31} = \frac{\overline{\varphi}_{C1}-\overline{\varphi}_{C2}}{C_1-C_2} - \Phi_{32}(C_1 + C_2)$; and $\Phi_{32} = \frac{1}{C_1-C_2}\left\{\frac{\overline{\varphi}_{C1}-\overline{\varphi}_{C2}}{C_1-C_2} - \frac{\overline{\varphi}_{C2}-\overline{\varphi}_{C3}}{C_2-C_3}\right\}$.

The gross mean values of MRR and SR are

$$(MRR)_{mean} = 0.4389\ g/\text{min},\ \ (SR)_{mean} = 1.33\ \mu m \tag{10}$$

Relations (4) to (9) are developed from the three mean values and corresponding level values of each input process parameter. Mean value plots of the output responses confirm the above quadratic relations (4) to (9). It should be noted that in a truly quadratic model as being followed in the response surface methodology (RSM), cross-terms can be expected in the empirical relations while representing the output response in terms of input process variables. In the present study, the empirical relations (2) and (3) are developed for MRR and SR using the additive law and the quadratic relations (4) to (9) obtained from the mean value plots. Eqs. (2) and (3) provide the results same as those obtained from the additive law [39] given in Eq. (1). Estimates of MRR and SR in Figs. 1 and 2 indicate reasonably in good agreement with test results [30].

As per the Taguchi design of experiments, the number of experiments ($N_{Taguchi}$) for the selected input parameters and levels is

Table 3
Levels of process parameters with a fictitious parameter in n-PMEDM of INCONEL800 with copper electrode.

Assignment levels				
Input parameters	Designated Factor	Level-1	Level-2	Level-3
Peak Current (Amp)	A	5	10	15
Pulse- on-time (µs)	B	6	7	8
Pulse-off-time (µs)	C	3	4	5
Fictitious	D	F1	F2	F3

Estimates of output responses with fictitious parameter D								
Test Run	Levels of input parameters				Output responses			
					MRR (g/min)		SR (µm)	
	A	B	C	D	Test [30]	Estimate Eq. (1)	Test [30]	Estimate Eq. (1)
1	1	1	1	1	0.1148	0.1149	0.98	0.9800
2	1	2	2	2	0.3150	0.3150	1.18	1.1800
3	1	3	3	3	0.5589	0.5590	1.33	1.3299
4	2	1	2	3	0.2258	0.2259	1.21	1.2099
5	2	2	3	1	0.4347	0.4347	1.49	1.4900
6	2	3	1	2	0.6009	0.6010	1.27	1.2700
7	3	1	3	2	0.4609	0.4609	1.54	1.5399
8	3	2	1	3	0.4920	0.4921	1.34	1.3400
9	3	3	2	1	0.7472	0.7472	1.63	1.6300

Table 4
ANOVA for MRR and SR including a fictitious parameter (D).

Input Parameters	1-Mean	2-Mean	3-Mean	Sum of squares	% contribution
Material removal rate (MRR)					
A	0.3296	0.4205	0.5667	0.0859	28.2
B	0.2672	0.4139	0.6357	0.2065	67.7
C	0.4026	0.4293	0.4848	0.0106	3.5
D	0.4322	0.4589	0.4256	0.0019	0.6
Surface roughness (SR)					
A	1.1633	1.3233	1.5033	0.1736	53.8
B	1.2433	1.3367	1.4100	0.0419	13.0
C	1.1967	1.3400	1.4533	0.0993	30.8
D	1.3667	1.3300	1.2933	0.0081	2.4

$$N_{Taguchi} = 1 + (\text{Number of factors}) \times (\text{Number of Levels} - 1) \tag{11}$$

in the present nine test runs (i.e., $N_{Taguchi} = 9$) and 3 levels, Eq. (11) allows four factors.

A fictitious factor (fourth factor) D is introduced as in Ref. [34] for EDM of INCONEL800 in Table 3 and performed ANOVA in Table 4.

1-Mean, 2-Mean and 3-Mean values of MRR for the fictitious parameter D are: $\overline{\psi}_{D1} = (\psi_1 + \psi_5 + \psi_9)/3 = 0.4322$; $\overline{\psi}_{D2} = (\psi_2 + \psi_6 + \psi_7)/3 = 0.4589$; and $\overline{\psi}_{D3} = (\psi_3 + \psi_4 + \psi_8)/3 = 0.4256$, respectively. Denoting the differential response $\Delta\overline{\psi}_{Di}(i = 1\ to\ 3)$ to the i^{th} level of D and evaluating the sum of squares of deviation from the mean for D for MRR is:

$$\psi_{SOS\ (D)} = 3\sum_{i=1}^{3}(\Delta\overline{\psi}_{Di})^2 = 3\sum_{i=1}^{3}(\overline{\psi}_{Di} - \psi_{mean})^2 = 0.0019.$$

%Contribution of D to the total variation for MRR obtained is: $\%C_D = 100 \times \frac{\psi_{SOS\ (D)}}{\psi_{SOS\ (T)}} = 0.6$. $Error\ (\%) = 100 - (\%C_A + \%C_B + \%C_C + \%C_D) = 100 - (28.2 + 67.7 + 3.5 + 0.6) = 0$.

1-Mean, 2-Mean and 3-Mean values of SR for the fictitious parameter D are: $\overline{\varphi}_{D1} = (\varphi_1 + \varphi_5 + \varphi_9)/3 = 1.3667$; $\overline{\varphi}_{D2} = (\varphi_2 + \varphi_6 + \varphi_7)/3 = 1.33$; and $\overline{\varphi}_{D3} = (\varphi_3 + \varphi_4 + \varphi_8)/3 = 1.2933$, respectively. Denoting the differential response $\Delta\overline{\varphi}_{Di}(i = 1\ to\ 3)$ to the i^{th} level of D and evaluating the sum of squares of deviation from the mean for D for SR is:

$$\varphi_{SOS\ (D)} = 3\sum_{i=1}^{3}(\Delta\overline{\varphi}_{Di})^2 = 3\sum_{i=1}^{3}(\overline{\varphi}_{Di} - \varphi_{mean})^2 = 0.0081.$$

%Contribution of D to the total variation for SR obtained is: $\%C_D = 100 \times \frac{\varphi_{SOS\ (D)}}{\varphi_{SOS\ (T)}} = 2.4$. $Error\ (\%) = 100 - (\%C_A + \%C_B + \%C_C + \%C_D) = 100 - (53.8 + 13.0 + 30.8 + 2.4) = 0$.

Table 5
Estimates of MRR for INCONEL800 with copper electrode.

S. No.	Input parameters			Material removal rate, MRR (g/min)			
	A (Amp)	B (μs)	C (μs)	Test [30]	Estimate Eq. (2)	Expected Range	
						Lower bound	Upper bound
1	5	6	3	0.11438	0.1216	0.1083	0.1416
2	5	6	4	0.13967	0.1483	0.135	0.1683
3	5	6	5	0.15019	0.2038	0.1905	0.2238
4	10	6	3	0.21576	0.2125	0.1992	0.2325
5	10	6	4	0.22548	0.2392	0.2259	0.2592
6	10	6	5	0.25345	0.2947	0.2814	0.3147
7	15	6	3	0.38793	0.3587	0.3454	0.3787
8	15	6	4	0.43584	0.3854	0.3721	0.4054
9	15	6	5	0.46086	0.4409	0.4276	0.4609
10	5	7	3	0.28472	0.2683	0.255	0.2883
11	5	7	4	0.3156	0.295	0.2817	0.315
12	5	7	5	0.33025	0.3505	0.3372	0.3705
13	10	7	3	0.35302	0.3592	0.3459	0.3792
14	10	7	4	0.38582	0.3859	0.3726	0.4059
15	10	7	5	0.43447	0.4414	0.4281	0.4614
16	15	7	3	0.4927	0.5054	0.4921	0.5254
17	15	7	4	0.5221	0.5321	0.5188	0.5521
18	15	7	5	0.58115	0.5876	0.5743	0.6076
19	5	8	3	0.50203	0.4901	0.4768	0.5101
20	5	8	4	0.53702	0.5168	0.5035	0.5368
21	5	8	5	0.55829	0.5723	0.559	0.5923
22	10	8	3	0.60079	0.581	0.5677	0.601
23	10	8	4	0.64298	0.6077	0.5944	0.6277
24	10	8	5	0.67097	0.6632	0.6499	0.6832
25	15	8	3	0.69663	0.7272	0.7139	0.7472
26	15	8	4	0.74722	0.7539	0.7406	0.7739
27	15	8	5	0.79346	0.8094	0.7961	0.8294

Table 6
Estimates of SR for INCONEL800 with copper electrode.

S. No.	Input parameters			Surface roughness, SR (μm)			
	A (Amp)	B (μs)	C (μs)	Test [30]	Estimate Eq. (3)	Expected Range	
						Lower bound	Upper bound
1	5	6	3	0.98	0.9433	0.9066	0.98
2	5	6	4	1.04	1.0866	1.0499	1.1233
3	5	6	5	1.18	1.1999	1.1632	1.2366
4	10	6	3	1.12	1.1033	1.0666	1.14
5	10	6	4	1.21	1.2466	1.2099	1.2833
6	10	6	5	1.37	1.3599	1.3232	1.3966
7	15	6	3	1.27	1.2833	1.2466	1.32
8	15	6	4	1.34	1.4266	1.3899	1.4633
9	15	6	5	1.54	1.5399	1.5032	1.5766
10	5	7	3	1.08	1.0367	1	1.0734
11	5	7	4	1.18	1.18	1.1433	1.2167
12	5	7	5	1.26	1.2933	1.2566	1.33
13	10	7	3	1.23	1.1967	1.16	1.2334
14	10	7	4	1.35	1.34	1.3033	1.3767
15	10	7	5	1.49	1.4533	1.4166	1.49
16	15	7	3	1.34	1.3767	1.34	1.4134
17	15	7	4	1.54	1.52	1.4833	1.5567
18	15	7	5	1.75	1.6333	1.5966	1.67
19	5	8	3	1.17	1.11	1.0733	1.1467
20	5	8	4	1.26	1.2533	1.2166	1.29
21	5	8	5	1.33	1.3666	1.3299	1.4033
22	10	8	3	1.27	1.27	1.2333	1.3067
23	10	8	4	1.38	1.4133	1.3766	1.45
24	10	8	5	1.53	1.5266	1.4899	1.5633
25	15	8	3	1.58	1.45	1.4133	1.4867
26	15	8	4	1.63	1.5933	1.5566	1.63
27	15	8	5	1.78	1.7066	1.6699	1.7433

Using Eq. (1) and the mean values in Table 4 estimates of MRR and SR with inclusion of fictitious parameter (D) in Table 3 are close to the test results. This may be the reason why the Error (%) is zero with inclusion of the fictitious parameter (D). For a specific case (Test run-4 in Table 3) estimates of MRR and SR utilizing Eq. (1) and the mean values in Table 4 are presented below. The process parameters in test run-4 of Table 3 are $A_2\ B_1\ C_2\ D_3$ and $n_p = 4$. For these process parameters, estimates of MRR and SR using Eq. (1) are

$MRR = \widehat{\phi} = \phi(X_1^2 = A_2,\ X_2^1 = B_1,\ X_3^2 = C_2,\ X_4^3 = D_3) = \phi_{X1}^2 + \phi_{X2}^1 + \phi_{X3}^2 + \phi_{X4}^3 - 3 \times \phi_{mean} = \overline{\psi}_{A2} + \overline{\psi}_{B1} + \overline{\psi}_{C2} + \overline{\psi}_{D3} - 3 \times \psi_{mean} = 0.4205 + 0.2672 + 0.4293 + 0.4256 - 3 \times 0.4389 = 0.2259$ g/min.

$SR = \widehat{\phi} = \phi(X_1^2 = A_2,\ X_2^1 = B_1,\ X_3^2 = C_2,\ X_4^3 = D_3) = \phi_{X1}^2 + \phi_{X2}^1 + \phi_{X3}^2 + \phi_{X4}^3 - 3 \times \phi_{mean} = \overline{\varphi}_{A2} + \overline{\varphi}_{B1} + \overline{\varphi}_{C2} + \overline{\varphi}_{D3} - 3 \times \varphi_{mean} = 1.3233 + 1.2433 + 1.34 + 1.2933 - 3 \times 1.33 = 1.2099 \mu m.$

For the process parameters in test run-4 of Table 3 ($A_2\ B_1\ C_2\ D_3$), estimates of MRR and SR from Eq. (1) are 0.2259 g/min and 1.2099 μm respectively, whereas the test results are 0.2258 g/min and 1.21 μm respectively. It should be noted that inclusion of fictitious parameter (D) makes the estimates of MRR and Sr close to the test results in Table 3. Careful examination of Eq. (1) indicates one of the following corrections due to fictitious parameter (D) to be considered while estimating MRR:

$\Delta\overline{\psi}_{D1} = \overline{\psi}_{D1} - \psi_{mean} = 0.4322 – 0.4389 = -0.0067$

$\Delta\overline{\psi}_{D2} = \overline{\psi}_{D2} - \psi_{mean} = 0.4589 – 0.4389 = 0.02$

$\Delta\overline{\psi}_{D3} = \overline{\psi}_{D3} - \psi_{mean} = 0.4256 – 0.4389 = -0.0133$

Similarly, one of the following corrections due to fictitious parameter (D) to be considered while estimating SR:

$\Delta\overline{\varphi}_{D1} = \overline{\varphi}_{D1} - \varphi_{mean} = 1.3667 – 1.33 = 0.0367$

$\Delta\overline{\varphi}_{D2} = \overline{\varphi}_{D2} - \varphi_{mean} = 1.33 – 1.33 = 0$

$\Delta\overline{\varphi}_{D3} = \overline{\varphi}_{D3} - \varphi_{mean} = 1.2933 – 1.33 = -0.0367$

It can be verified from the estimates of the output responses (viz., MRR and SR) without and with fictitious parameter (D) in Tables 1 and 3 that adding the appropriate correction to the estimates in Table 1 results the estimates of Table 3, which are close to the test results. For obtaining the expected range of the output responses, the minimum and maximum correction values should be added. In the present study, the minimum and maximum correction values to MRR are -0.0133 g/min and 0.02 g/min respectively. To SR, the minimum and maximum correction values are -0.0367 μm and 0.0367 μm respectively. These corrections can be applied to the estimates of MRR and SR using empirical relations (2) and (3).

Tables 5 and 6 present the expected range of MRR and SR by considering the levels of lowest and highest mean values of the output responses to the fictitious parameter. Test results in Tables 5 and 6 are found to be within the expected range.

3. Results & discussion

The process parameters for maximum MRR and minimum SR from the ANOVA results are found to be different. A simple and reliable multi-objective optimization procedure following the Taguchi approach is presented below for tracing a set of optimal process parameters. Since MRR and SR are two different output responses, they must be functionally represented in dimensionless form. From the ANOVA Table 4, the maximum MRR and SR estimated are: $(MRR)_{max} = 0.8294$ g/min; and $(SR)_{max} = 1.743333$ μm. It can be verified that minimum values of $\zeta_1 \left(\equiv \frac{(MRR)_{max}}{MRR} - 1 \right)$ and $\zeta_2 \left(\equiv \frac{SR}{(SR)_{max}} \right)$ tend to maximum MRR and minimum SR. Introducing the positive weighing factors ω_1 and ω_2 (which satisfy $\omega_1 + \omega_2 = 1$), one can write a single function (ζ) to optimize MRR and SR in the form

$$\zeta = \omega_1\ \zeta_1 + \omega_2\ \zeta_2 \qquad (12)$$

It should be noted from Eq. (12) that in the multi-objective treatment the two responses (ζ_1, ζ_2) are combined into a single objective function (ζ) by a linear weighing. The weight for each response should be based on the judgements of the end user or the decision maker. Minimization of ζ provides the maximum MRR and minimum SR for a set of process

Table 7
Variation of the multi-objective optimization function (ζ) with weighing factors ω_1 andω_2 for the output responses of Table 1. $(MRR)_{max}$= 0.8294 g/min; $(SR)_{max}$= 1.743333 μm; $\omega_1 \geq 0$, $\omega_2 \geq 0$ and $\omega_1 + \omega_2 = 1$.

(a) Normalized parameters ζ_1 and ζ_2

Test runs	Levels of Input Parameters			MRR (g/min)	$\zeta_1 = \frac{(MRR)_{max}}{MRR} - 1$	SR (μm)	$\zeta_2 = \frac{SR}{(SR)_{max}}$
	A	B	C				
1	1	1	1	0.11438	6.2247	0.98	0.5621
2	1	2	2	0.31560	1.6330	1.18	0.6769
3	1	3	3	0.55829	0.4840	1.33	0.7629
4	2	1	2	0.22548	2.6732	1.21	0.6941
5	2	2	3	0.43447	0.9080	1.49	0.8547
6	2	3	1	0.60079	0.3803	1.27	0.7285
7	3	1	3	0.46089	0.7995	1.54	0.8834
8	3	2	1	0.49270	0.6858	1.34	0.7686
9	3	3	2	0.74722	0.1100	1.63	0.9350

(b) Multi objective optimization function, $\zeta = \omega_1 \zeta_1 + \omega_2 \zeta_2$ for the specified weighing factors ω_1 and $\omega_2 = 1 - \omega_1$.

Test runs	Multi-objective optimization function (ζ)				
	$\omega_1 = 1$	$\omega_1 = 0.75$	$\omega_1 = 0.5$	$\omega_1 = 0.25$	$\omega_1 = 0$
1	6.2247	4.8091	3.3934	1.9778	0.5621
2	1.6330	1.3940	1.1549	0.9159	0.6769
3	0.4840	0.5537	0.6234	0.6932	0.7629
4	2.6732	2.1784	1.6836	1.1888	0.6941
5	0.9080	0.8947	0.8813	0.8680	0.8547
6	0.3803	0.4673	0.5544	0.6414	0.7285
7	0.7995	0.8205	0.8414	0.8624	0.8834
8	0.6858	0.7065	0.7272	0.7479	0.7686
9	0.1100	0.3163	0.5225	0.7287	0.9350

parameters. It should be noted that for the specified $\omega_1 = 1$ ($\Rightarrow \omega_2 = 0$), minimization of ζ yields only the maximum MRR and the optimum input process parameters are $A_3B_3C_3$. For the specified $\omega_2 = 1$ ($\Rightarrow \omega_1 = 0$), minimization of ζ yields only the minimum SR and the optimum input process parameters are $A_1B_1C_1$. The above mentioned optimum input process parameters for two special cases can be identified from the results in Table 2 with bold numerals. To achieve common optimal process conditions, one has to specify weighing factors ω_1 andω_2. By specifying weighing factors ($\omega_1 = 1$, 0.75, 0.5, 0.25, 0, and$\omega_2 = 1 - \omega_1$) Table 7 gives the values of ζ generated from Eq. (12) for each test run. ANOVA is performed on ζ in Table 8 for the 9 test runs and identified the optimal

Table 8
ANOVA on the multi-objective optimization function, ζ for the specified weighing factors ω_1 and ω_2.

Input process parameters	1-mean	2-mean	3-mean
$\omega_1 = 1.0$; $\omega_2 = 0.0$			
A	2.7806	1.3205	**0.5318**
B	3.2325	1.0756	**0.3248**
C	2.4303	1.4721	**0.7305**
$\omega_1 = 0.75$; $\omega_2 = 0.25$			
A	2.2523	1.1801	**0.6144**
B	2.6027	0.9984	**0.4458**
C	1.9943	1.2962	**0.7563**
$\omega_1 = 0.5$; $\omega_2 = 0.5$			
A	1.7239	1.0398	**0.6971**
B	1.9728	0.9212	**0.5668**
C	1.5583	1.1204	**0.7821**
$\omega_1 = 0.25$; $\omega_2 = 0.75$			
A	1.1956	0.8994	**0.7797**
B	1.3430	0.8439	**0.6878**
C	1.1224	0.9445	**0.8079**
$\omega_1 = 0.0$; $\omega_2 = 1.0$			
A	**0.6673**	0.7591	0.8623
B	**0.7132**	0.7667	0.8088
C	**0.6864**	0.7686	0.8337

Bold indicates the level of the optimal process parameters.

Table 9
Surface roughness and machining time in robotic end milling process of AA6005 for the assigned levels of control factors.

Assignment levels

Control factors (Input parameters)	Designated Factor	Level -1	Level-2	Level-3
Tool path strategy	X_1	Raster	Zig-Zag	Offset
Spindle speed (rpm)	X_2	10000	12000	14000
Feed rate (mm.min)	X_3	1000	800	600
Fictitious	X_4	F1	F2	F3

Estimates of output responses with fictitious parameter D

Test Run	Levels of input parameters				Output responses			
					Surface roughness, SR (μm)		Machining time, MT (min)	
	X_1	X_2	X_3	X_4	Test [40]	Estimate Eq. (1)	Test [40]	Estimate Eq. (1)
1	1	1	1	1	0.8211	0.8211	0.78	0.78
2	1	2	2	2	0.5833	0.5833	0.93	0.93
3	1	3	3	3	0.4391	0.4391	1.17	1.17
4	2	1	2	3	0.7107	0.7107	0.88	0.88
5	2	2	3	1	0.5521	0.5521	1.13	1.13
6	2	3	1	2	0.9093	0.9093	0.73	0.73
7	3	1	3	2	0.8044	0.8044	2.05	2.05
8	3	2	1	3	0.7184	0.7184	1.28	1.28
9	3	3	2	1	0.5207	0.5207	1.57	1.57

process parameters as $A_3B_3C_3$ for $0.25 \leq \omega_1 \leq 1$ and$\omega_2 = 1 - \omega_1$. The optimal process parameters for minimumζ recommended are: 15 ampere current (A_3), 8 μs pulse-on-time (B_3) and 5μs pulse-off-time (C_3). The corresponding values of MRR and SR from tests are 0.79346 g/min and 1.78 μm respectively, which are within/close to the expected range 0.7961–0.8294 g/min and 1.6699–1.7433 μm respectively.

Taguchi technique adopted here is quite simple and easy in solving the multi-objective optimization problem to identify optimal process parameters in n-PMEDM of INCONEL800 with copper electrode. Little improvement in MRR is noticed with coated electrodes [30]. In order to examine its adequacy further, investigations made in [40] on robotic end milling process of AA6005 applying the signal-to-noise (S/N) ratio transformation to the output responses and utilizing the Taguchi-Grey relational optimization method is considered as a case study.

Unnikrishna Pillai et al. [40] have examined the influence of process parameters (viz., tool path strategic, spindle speed and feed rate) on the machining time (MT) and surface roughness (SR), and presented a set of optimal process parameters for robotic end milling process of AA6005 applying the signal-to-noise (S/N) ratio transformation to the output responses and using the Taguchi-Grey relational optimization method. They have assigned three levels for the three factors (viz., tool path strategy (X_1), spindle speed (X_2) and feed rate (X_3)) and performed end milling operations on KukaQUANTECKR120R2700 6-axis robotic machining centre as per the Taguchi's L_9 orthogonal array. A single flute AZSTAR uncoated solid carbide tool (having 12 mm diameter, 0.3× 45° corner Chamfer, 84 mm length, 25 mm length of cut and 20° helix) is used for machining the work-piece. Alicona Infinite focus microscope with a lambda filter (cut-off wavelength) of 250 μm is used to measure the surface roughness for each test-run. Machining time for each test-run is recorded from the machining centre. Machining is performed with 1.2 mm axial depth of cut. A set of the optimal robotic end milling process parameters is recommended to improve production and product quality by minimizing the machining time and lowering the surface roughness.

Table 9 gives the levels of process parameters and the output responses (viz., SR and MT) as per Taguchi's L_9 orthogonal array. ANOVA is done for the optimum process parameters to obtain minimum SR and minimum MT. The ANOVA results of Table 10 indicate the influence of process parameters on SR as feed rate (X_3) with 46.3 % contribution, spindle speed (X_2) with 25.2 % contribution and tool path strategy (X_1)

Table 10
ANOVA Surface roughness (SR) and machining time (MT) in robotic end milling process of AA6005.

Surface roughness (SR)					
Gross mean = 0.6732 and Total sum of squares = 0.1991					
Input Parameters	1-Mean	2-Mean	3-Mean	Sum of squares	% contribution
X_1	**0.6145**	0.7240	0.6811	0.01828	9.2
X_2	0.7787	**0.6179**	0.6230	0.05012	25.2
X_3	0.8162	0.6049	**0.5985**	0.09212	46.3
X_4	0.6313	0.7656	0.6227	0.03855	19.4
Machining time (MT)					
Gross mean = 1.1689 and Total sum of squares = 1.4355					
Input Parameters	1-Mean	2-Mean	3-Mean	Sum of squares	% contribution
X_1	0.96	**0.9133**	1.6333	0.97395	67.8
X_2	1.2366	**1.1133**	1.1566	0.02348	1.6
X_3	**0.93**	1.1266	1.45	0.41362	28.8
X_4	1.16	1.2366	1.11	0.02442	1.7

Table 11
Estimates of surface roughness (SR) in robotic end milling process of AA6005. Corrections for lower and upper bounds: -0.0505 and 0.0924.

S. No.	Levels of Input parameters			Surface roughness, SR (μm)			
	X_1	X_2	X_3	Test [40]	Estimate Eq. (1)	Expected Range	
						Lower bound	Upper bound
1	1	1	1	0.8211	0.8630	0.8125	0.9554
2	1	1	2		0.6516	0.6011	0.7441
3	1	1	3		0.6453	0.5948	0.7377
4	1	2	1		0.7022	0.6517	0.7946
5	1	2	2	0.5833	0.4908	0.4403	0.5833
6	1	2	3		0.4845	0.4340	0.5769
7	1	3	1		0.7073	0.6568	0.7997
8	1	3	2	0.4879	0.4959	0.4454	0.5884
9	1	3	3	0.4391	0.4896	0.4391	0.5820
10	2	1	1		0.9725	0.9220	1.0650
11	2	1	2	0.7107	0.7612	0.7107	0.8536
12	2	1	3		0.7548	0.7043	0.8472
13	2	2	1		0.8117	0.7612	0.9042
14	2	2	2		0.6004	0.5499	0.6928
15	2	2	3	0.5521	0.5940	0.5435	0.6864
16	2	3	1	0.9093	0.8168	0.7663	0.9093
17	2	3	2		0.6055	0.5550	0.6979
18	2	3	3		0.5991	0.5486	0.6915
19	3	1	1		0.9297	0.8792	1.0221
20	3	1	2		0.7183	0.6678	0.8107
21	3	1	3	0.8044	0.7119	0.6614	0.8044
22	3	2	1	0.7184	0.7689	0.7184	0.8613
23	3	2	2		0.5575	0.5070	0.6499
24	3	2	3		0.5511	0.5006	0.6436
25	3	3	1		0.7740	0.7235	0.8664
26	3	3	2	0.5207	0.5626	0.5121	0.6550
27	3	3	3		0.5562	0.5057	0.6487

with 9.2 % contributions. Tool path strategy (X_1) has 67.8 % contribution on SR, whereas the spindle speed (X_2) and feed rate (X_3) have 1.6 %, and 28.8 % contributions. Estimates of SR and MT with inclusion of the fictitious parameter (X_4) from Eq. (1) in Table 9 are close to the test results. Tables 11 and 12 present the expected range of SR and MT for the full factorial design of experiments by considering the levels of lowest and highest mean values of the output responses to the fictitious parameter. Test results in Tables 11 and 12 are found to be within the expected range. The confirmation experiment results in [40] (S.No.8 of Tables 11 and 12) are also found to be within the expected range.

From the ANOVA Table 10, the maximum SR and MT estimated are: $(SR)_{max}$ = 1.065 μm; $(MT)_{max} = 2.05$ min. It can be verified that minimum

Table 12
Estimates of machining time (MT) in robotic end milling process of AA6005. Corrections for lower and upper bounds: -0.0589 and 0.0678.

S. No.	Levels of Input parameters			Machining time, MT (min)			
	X_1	X_2	X_3	Test [40]	Estimate Eq. (1)	Expected Range	
						Lower bound	Upper bound
1	1	1	1	0.78	0.7888	0.7299	0.8566
2	1	1	2		0.9855	0.9266	1.0533
3	1	1	3		1.3088	1.2499	1.3766
4	1	2	1		0.6655	0.6066	0.7333
5	1	2	2	0.93	0.8622	0.8033	0.9300
6	1	2	3		1.1855	1.1266	1.2533
7	1	3	1		0.7088	0.6499	0.7766
8	1	3	2	0.933	0.9055	0.8466	0.9733
9	1	3	3	1.17	1.2288	1.1699	1.2966
10	2	1	1		0.7422	0.6833	0.8100
11	2	1	2	0.88	0.9388	0.8799	1.0066
12	2	1	3		1.2622	1.2033	1.3300
13	2	2	1		0.6188	0.5599	0.6866
14	2	2	2		0.8155	0.7566	0.8833
15	2	2	3	1.13	1.1388	1.0799	1.2066
16	2	3	1	0.73	0.6622	0.6033	0.7300
17	2	3	2		0.8588	0.7999	0.9266
18	2	3	3		1.1822	1.1233	1.2500
19	3	1	1		1.4622	1.4033	1.5300
20	3	1	2		1.6588	1.5999	1.7266
21	3	1	3	2.05	1.9822	1.9233	2.0500
22	3	2	1	1.28	1.3388	1.2799	1.4066
23	3	2	2		1.5355	1.4766	1.6033
24	3	2	3		1.8588	1.7999	1.9266
25	3	3	1		1.3822	1.3233	1.4500
26	3	3	2	1.57	1.5788	1.5199	1.6466
27	3	3	3		1.9022	1.8433	1.9700

Table 13
Variation of the multi-objective optimization function, $\zeta\ (= \omega_1\zeta_1 + \omega_2\zeta_2)$ with weighing factors ω_1 andω_2 for the output responses of Table 3. $(SR)_{max}$= 1.065 μm; $(MT)_{max} = 2.05$ min. $\omega_1 \geq 0$, $\omega_2 \geq 0$ and $\omega_1 + \omega_2 = 1$.

(a) Normalized parameters ζ_1 and ζ_2

Test runs	Levels of Input Parameters			SR (μm)	$\zeta_1 = \frac{SR}{(SR)_{max}}$	MT (min)	$\zeta_2 = \frac{MT}{(MT)_{max}}$
	X_1	X_2	X_3				
1	1	1	1	0.8211	0.7710	0.78	0.3805
2	1	2	2	0.5833	0.5477	0.93	0.4537
3	1	3	3	0.4391	0.4123	1.17	0.5707
4	2	1	2	0.7107	0.6673	0.88	0.4293
5	2	2	3	0.5521	0.5184	1.13	0.5512
6	2	3	1	0.9093	0.8538	0.73	0.3561
7	3	1	3	0.8044	0.7553	2.05	1.0000
8	3	2	1	0.7184	0.6746	1.28	0.6244
9	3	3	2	0.5207	0.4889	1.57	0.7659

(b) Multi objective optimization function, $\zeta = \omega_1\ \zeta_1 + \omega_2\ \zeta_2$ for the specified weighing factors ω_1 and $\omega_2 = 1 - \omega_1$.

Test runs	Multi-objective optimization function (ζ)				
	$\omega_1 = 1$	$\omega_1 = 0.75$	$\omega_1 = 0.5$	$\omega_1 = 0.25$	$\omega_1 = 0$
1	0.7710	0.6734	0.5757	0.4781	0.3805
2	0.5477	0.5242	0.5007	0.4772	0.4537
3	0.4123	0.4519	0.4915	0.5311	0.5707
4	0.6673	0.6078	0.5483	0.4888	0.4293
5	0.5184	0.5266	0.5348	0.5430	0.5512
6	0.8538	0.7294	0.6050	0.4805	0.3561
7	0.7553	0.8165	0.8777	0.9388	1.0000
8	0.6746	0.6620	0.6495	0.6369	0.6244
9	0.4889	0.5582	0.6274	0.6966	0.7659

values of$\zeta_1 = \frac{SR}{(SR)_{max}}$ and $\zeta_2 = \frac{MT}{(MT)_{max}}$ tend to minimum SR and minimum MT. Introducing the positive weighing factors ω_1 and ω_2 (which satisfy$\omega_1 + \omega_2 = 1$), one can write a single function (ζ) to optimize SR and

Table 14
ANOVA on the multi-objective optimization function, $\zeta\ (= \omega_1\zeta_1 + \omega_2\zeta_2)$ for the specified weighing factors ω_1 and ω_2.

Input process parameters	1-mean	2-mean	3-mean
$\omega_1 = 1.0;\ \omega_2 = 0.0$			
X_1	**0.5770**	0.6798	0.6396
X_2	0.7312	**0.5802**	0.5850
X_3	0.7664	0.5680	**0.5620**
$\omega_1 = 0.75;\ \omega_2 = 0.25$			
X_1	**0.5498**	0.6213	0.6789
X_2	0.6992	**0.5709**	0.5798
X_3	0.6883	**0.5634**	0.5983
$\omega_1 = 0.5;\ \omega_2 = 0.5$			
X_1	**0.5226**	0.5627	0.7182
X_2	0.6672	**0.5617**	0.5746
X_3	0.6101	**0.5588**	0.6347
$\omega_1 = 0.25;\ \omega_2 = 0.75$			
X_1	**0.4955**	0.5041	0.7575
X_2	0.6352	**0.5524**	0.5694
X_3	**0.5319**	0.5542	0.6710
$\omega_1 = 0.0;\ \omega_2 = 1.0$			
X_1	0.4683	**0.4455**	0.7967
X_2	0.6033	**0.5431**	0.5642
X_3	**0.4537**	0.5496	0.7073

Bold indicates the level of the optimal process parameters.

Table 15
Optimum end milling process parameters for AA6005.

Weighing factors ($\omega_1 + \omega_2 = 1$)	Levels of process parameters			Expected range of output responses	
	X_1	X_2	X_3	SR (μm)	MT (min)
$\omega_1 = 1.0;\ \omega_2 = 0.0$	1	2	3	0.4340–0.5769	1.1266–1.2533
@$\omega_1 = 0.75;\ \omega_2 =$ 0.25 (First option)	1	2	2	0.4403–0.5833 (0.5833)*	0.8033–0.9300 (0.93)
$\omega_1 = 0.75;\ \omega_2 =$ 0.25 (Second option)	1	3	2	0.4454–0.5884 (0.4879)	0.8466–0.9733 (0.933)
$\omega_1 = 0.5;\ \omega_2 = 0.5$	1	2	2	0.4403–0.5833 (0.5833)	0.8033–0.9300 (0.93)
$\omega_1 = 0.25;\ \omega_2 =$ 0.75	1	2	1	0.6517–0.7946	0.6066–0.7333
$\omega_1 = 0.0;\ \omega_2 = 1.0$	2	2	1	0.7612–0.9042	0.5599–0.6866

* Test data [40].

MT as in Eq. (12):$\zeta = \omega_1\ \zeta_1 + \omega_2\ \zeta_2$. In this multi-objective treatment the two responses ($\zeta_1,\ \ \zeta_2$) are combined into a single objective function (ζ) by a linear weighing. The weight for each response should be based on the judgements of the end user or the decision maker. Minimization of ζ provides the minimum SR and minimum MT for a set of process parameters. To achieve common optimal process conditions, one has to specify weighing factors ω_1 and ω_2. By specifying weighing factors ($\omega_1 =$ 1, 0.75, 0.5, 0.25, 0, and $\omega_2 = 1 - \omega_1$) Table 13 gives the values of ζ for each test run. ANOVA is performed on ζ in Table 14 for the 9 test runs and the possible optimal process parameters are presented in Table 15.

It should be noted that for the specified $\omega_1 = 1\ (\Rightarrow \omega_2 = 0)$, minimization of ζ yields only the minimum SR for the process parameters: tool path strategy, $X_1^1 =$ Raster; spindle speed, $X_2^2 = 12000$ rpm; and feed rate, $X_3^3 = 600$ mm min. For the specified $\omega_2 = 1\ (\Rightarrow \omega_1 = 0)$, minimization of ζ yields only the minimum MT for the process parameters: $X_1^2 =$ zig-zag; $X_2^2 = 12000$ rpm; and $X_3^1 = 1000$ mm min. For the above two special cases of single objective optimization process, the process parameters can be identified directly from the results in Table 10 with bold numerals. The process parameters for minimum SR and minimum MT from the ANOVA results are found to be different. Hence, the problem demands the multi-objective optimization to have a set of optimal process parameters for achieving minimum SR and MT. Keeping in mind the importance of product quality and tolerating little enhancement in machining time, the optimal process parameters identified from Table 15 are: tool path strategy, $X_1^1 =$ Raster; spindle speed, $X_2^2 = 12000$ rpm; and feed rate, $X_3^2 = 800$ mm min for $0.5 \le \omega_1 \le 0.75$ and $\omega_2 = 1 - \omega_1$. Since, the third mean value of the multi-objective function, ζ corresponding to X_2 process parameter in Table 14 for $\omega_1 = 0.75$; $\omega_2 = 0.25$ is slightly higher, it is considered as the second option. However, the first option is recommended due to low values in the output responses when compared to that of the second option. This study demonstrates the adequacy of the present simplified analysis and confirms the test results of Ref. [40].

4. Conclusions

Present work deals with the specification of n-PMEDM process parameters to achieve optimal material removal rate (MRR) and surface roughness (SR) of INCONEL800 adopting the Taguchi approach. ANOVA is performed to assess the significance of the peak current, pulse-on-time and pulse-off-time on MRR and SR. Test results are found to be within/close to the expected range of MRR and SR. The developed empirical relations can be used for estimating MRR and SR to the specific input process parameters. Empirical relations are developed easily without use of the MINITAB Release-16 software. There is no additional advantage in applying the S/N ratio transformation to the single value of the output response. Taguchi approach suggests few experiments and provides the output responses for the full factorial design of experiments. Introducing fictitious parameter without enhancing the test runs in the modified Taguchi approach provides the expected range of the output responses. Optimal solution can be obtained utilizing the Taguchi approach by representing functionally the dissimilar quality characteristics of multiple responses to a single response characteristic after non-dimensioning them.

Declarations

Author contribution statement

Dharmendra B.V., Shyam Prasad Kodali & B. Nageswara Rao: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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