RESPONSE OPTIMIZATION IN WIRE ELECTRICAL DISCHARGE MACHINING FOR INCONEL 800: AN APPROACH BASED ON DESIRABILITY FUNCTION ANALYSIS

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Abstract

Wire Electrical Discharge Machining (WEDM) is a specialized thermal machining process capable of accurately machine parts with varying hardness or complex shapes and are very difficult to machine by conventional machining processes. This study outlines the development of model and its application to optimizing machining performances such as machining time and surface quality using Desirability Function Approach (DFA). The design matrix for the experiments is developed on the basis of 1/3 Fractional Factorial Design with no replication. Each experiment has been performed under different cutting conditions of pulse-on time, pulse-off time, peak current and spark gap set voltage. A composite desirability value is obtained for the multi-responses using individual desirability values from the DFA. Based on composite desirability value, the optimal levels of parameters have been identified. The optimal process parameters for individual response is also obtained by using Taguchi's signal to noise (S/N) ratio.

Keywords: WEDM, Desirability Function Approach, Taguchi.

1. Introduction

The difficulty in machining posted by the advanced engineering materials, such as titanium, stainless steel, high-strength temperature-resistant alloys, ceramics, fibre-reinforced composites etc. having higher strength, hardness, toughness, low machinability and other diverse mechanical properties has placed a demand for the non-traditional machining (NTM) processes. Among all the NTM processes, Wire Electrical Discharge Machining (WEDM) has become the most important one as it can be effectively used for electrically conductive materials, irrespective of their hardness and strength and can generate complex intricate designs with very good surface finish and close tolerances.

Inconel 800 is a nickel-based super alloy, which is used in the field of gas turbine components, cryogenic storage tanks, jet engines, pump bodies and parts, rocket motors and thrust reversers, nuclear fuel element spacers, hot extrusion tooling, high strength bolting, and down hole shafting (Donachie, M. J. et al. (2002), Daris, J. R. (1999), Kilian, R. et al. (1991)).

A lot of research has been directed towards machining of these hard materials by EDM during the last few decades. Different response parameters such as, surface roughness (SR), recast layer etc. of the EDM process are investigated during the. Hastelloy-X was experimented under various EDM conditions and analyzed in terms of surface integrity by Kang, S. H. et al. (2003). Bai, C. Y. (2007) investigated the effects of the electrical discharge alloying (EDA) process with Al-Mo composite electrode on improving the high temperature oxidation resistance of the Ni-based superalloy Haynes 230. Kuppan, P. et al. (2008) carried out experimental investigation using Taguchi method for small deep hole drilling of Inconel 718 using the EDM process and revealed that material removal rate (MRR) is more influenced by peak current, duty factor and electrode rotation, whereas depth average surface roughness (SR) is strongly influenced by peak current and pulse on-time. Bharti, P. S. et al. (2010) investigated the machining characteristics of Inconel 718 during die-sinking electric discharge machining process with copper as tool electrode. Discharge current and pulse on-time were identified as common influencing parameters for MRR, SR and tool wear ratio (TWR). Moreover it was found that duty cycle and tool electrode lift time was the least influential parameters. Reddy, C. B. et al. (2012) has elaborated the various developments made in the field of EDM for different materials for increasing the MRR and decreasing the tool wear as well as cost of machining. Daneshmand, S. et al. (2013) investigated the impacts of input parameters of electro discharge machining process including the voltage, pulse current, pulse on time and pulse off time on the output parameters of MRR, TWR, electrode wear rate (EWR) and SR for machining NiTi smart alloy using copper tools and de-ionized water as the dielectric. Experimental investigations were also carried out to study the effect of EDM parameters on MRR, EWR and surface quality (SQ) using different electrodes and workpiece materials. (Chhaniyara P. N. et al. (2014), Singh, H. et al. (2012)). Hewidy, M. S. et al. (2005) in their work highlighted mathematical models for correlating the inter-relationships of various Wire-EDM machining parameters of Inconel 601 material, such as peak current, duty factor, wire tension and water pressure on the MRR, wear ratio and SR. Va M. K. et al. (2010) demonstrated optimization of WEDM process parameters of Incoloy 800 super alloy with multiple performance characteristics and concluded that the Grey-Taguchi Method is most ideal and suitable for the parametric optimization of the Wire-Cut EDM process. Aggarwal, V. et al. (2015) used response surface methodology (RSM) to develop empirical models for predicting the cutting rate and the surface roughness while machining Inconel 718 alloy under different conditions. Chakravorty, R. et al. (2012) studied the correlation between the response variables and determined the optimal process conditions. Mahapatra, S. S. et al. (2007) established the optimized relationship between machining parameters and responses like cutting rate, SR and cutting width by employing non-linear regression analysis and geometric algorithm in WEDM operations of D2 tool steel with zinc-coated copper wire. Kondayya, D. et al. (2011) applied an integration of two evolutionary approaches namely genetic programming and non-dominated sorting genetic algorithm-II in WEDM process for modeling and optimization of cutting rate and SR while machining AISI D3 steel with uncoated brass wire. Thus, it can be seen that considerable research has been done in identifying and optimizing various machining parameters in WEDM. But such types of studies were mainly focused on improving single-quality characteristics at a time. Few researchers have tried for modelling and optimization of multiple quality characteristics in WEDM of Inconel 800. However, the performance of a machining process is often characterized by a group of responses. If more than one response comes into consideration it is very difficult to select the optimal setting which can achieve all quality requirements simultaneously. In order to tackle such a multi-response optimization problem, the present study has been proposed to find out the optimal setting of machining parameters for multiple output responses. Finally, the versatile use of Inconel 800 in different engineering applications together with comparatively easy availability of this alloy has prompted the selection of this material for present study.

2. Experimental details

2.1 Material and tool

Inconel 800 is an austenitic, solid-solution alloy and is composed of iron (minimum 39%), nickel (30-35%), chromium (30-35%), aluminium (0.15-0.6%), titanium (0.15-0.6%), manganese (0.1-1.5%) and traces of copper, sulphur and silicon. The chromium in the alloy imparts both aqueous and heat resistance. Iron provides resistance to internal oxidation. The nickel content maintains a ductile, austenitic structure.

The experimental study has been carried out on Electronica make 4-axis WEDM as shown in Figure 1. Inconel 800, available in the form of plates of 100mm×100mm×5mm is cut by EDM process into samples of size 25mm×25mm×5mm. A 0.25 mm diameter wire of brass with zinc coating, having tensile strength of 500 N/mm^2, has been used to perform all experiments. This zinc-coated wire consists of brass wire electroplated with high purity zinc. The high plating accuracy realizes faster machining and also provides a better surface finish on the work piece. The wire is fed from a wire supply wheel through an upper and lower roller along with an upper and lower guide. The wire is kept at a slight tension to avoid slag, given a feed of 4m/min and is

Figure 1: Electronica make 4-axis CNC sprincut WEDM.

collected in a wire take-up reel. Deionized water is used as the dielectric fluid for this experimentation. It is supplied continuously for maintaining a non-ionized zone between the cutting area of the workpiece and wire electrode edge. This dielectric fluid is pumped from the sump tank to the cutting area by means of two convergent nozzles (upper and lower nozzle) provided near to the cutting area.

2.2 Process parameters

A proper selection of machining parameters is a must for getting desired results. Thus, based on previous literatures and other sources, expert opinions and a series of experiments on different materials, four machining parameters or design variables, viz. pulse on time (T_{ON}), pulse off time (T_{OFF}), peak current (IP) and spark gap set voltage (SV) respectively, which intensely affect the output performance have been selected for the present study. Other parameters like wire feed (WF), wire tension (WT), spark gap feed (SF) etc. are kept constant. The following factors and levels of process parameters are selected for the present work as tabulated in Table 1.

Table 1: WEDM process parameters

Variable parameters	**Level 1**	**Level 2**	**Level 3**
T_{ON} (µs)	0.6	0.85	1.1
T_{OFF} (µs)	19	32	46
Peak current (IP)	210A	220A	230A
Spark gap voltage (SV)	15Volts	20Volts	25Volts
Fixed parameters	Wire Feed: 4 m/min.	Wire Tension: 600 grams	Peak voltage: 110V DC

2.3 Response Measurement

The output responses considered in this study are machining time and surface roughness. The measurement and calculation of responses based on the input parameters are described below.

2.3.1 Machining time

The time required for the desired operation to be completed is known as the machining time (T_m). As with other machining processes, in WEDM operation also, machining time determines its productivity. It depends on different process parameters as well the work-piece material. In the present investigation for each of the experiments, the machining time in minutes is collected with a stopwatch and recorded systematically.

2.3.2 Surface roughness

The surface roughness value of the machined surface is measured in order to analyze the surface finish quality. In EDM process, the surface produced consists of a large number of craters that are formed from the discharge energy. After machining the surface quality is measured using Taylor Hobson 3D Surface Profilometer as shown in Figure 2. On each machined surface, the surface roughness, expressed in µm is measured twenty times different locations and average value (R_a) of these measurements taken.

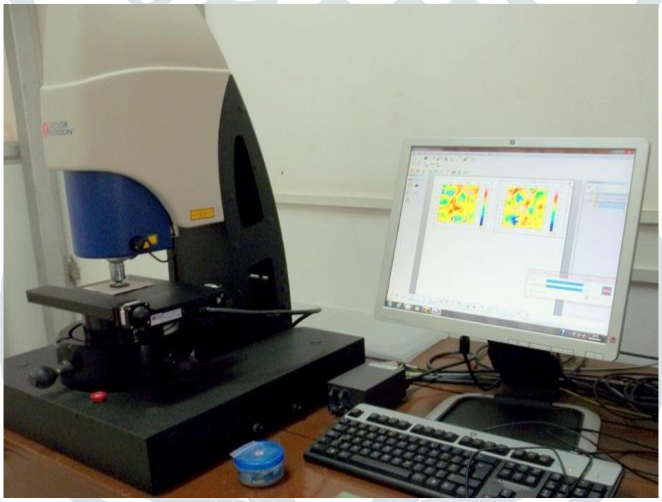

Figure 2: SR measurement with Taylor Hobson 3D Profilometer

3. Methodology

The design matrix for the experiments is developed on the basis of 1/3 Fractional Factorial Design with no replication thus resulting in a total of 27 numbers of experiments. The two responses of the experimentation, viz. machining time and surface roughness are measured, recorded and tabulated. These data are then subjected to optimization using Desirability Function Approach (DFA). DFA is first introduced by Harrington in 1965 and extended later by Derringer and Suich (1980). This method is a search-based optimization method which optimizes multiple response variables, individually and simultaneously, to find the optimum input variable settings (Mobin, et al. (2016)). Solving multi-response optimization problems starts with applying a technique for integrating multiple responses into a dimensionless function, called the overall desirability function (D). The approach is to first convert each response (y_i) into a dimensionless function, known as individual desirability function (d_i) that can be between zero and one. If the response y_i is at its target, the most desirable case is obtained i.e., $d_i = 1$, otherwise, $d_i = 0$ (the least desirable case). In the desirability function approach, there is a positive number, known as the weight factor (w), on which the shape of the desirability function for each response depends (Mobin, et al. (2016)). The individual desirability functions can be calculated based on the optimization functions, i.e. maximization or minimization. If the target (T_i) for the response y_i is a maximum value, the desirability is based on Equation (1) given below.

$$d_i = \begin{cases} 0 & y_i < L_i \\ \left(\frac{y_i - L_i}{T_i - L_i}\right)^w & L_i \le y_i \le T_i \\ 1 & y_i > T_i \end{cases} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

If the target is to get the minimum value, the desirability is based on the following equation shown below.

$$d_i = \begin{cases} 1 & y_i < L_i \\ \left(\frac{T_i - y_i}{T_i - L_i}\right)^w & L_i \le y_i \le T_i \\ 0 & y_i > T_i \end{cases} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Finally, if the target is located between the lower (L_i) and upper (U_i) limits, the desirability is based on Equation (3).

$$d_i = \begin{cases} 0 & y_i < L_i \\ \left(\frac{y_i - L_i}{T_i - L_i}\right)^w & L_i \le y_i \le T_i \\ \left(\frac{U_i - y_i}{U_i - L_i}\right)^w & T_i \le y_i \le U_i \\ 0 & y_i > U_i \end{cases} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Next, the individual desirability functions can be integrated as overall (composite or aggregated) desirability (D), which can be between 0 and 1. It is the weighted geometric mean of all the previously defined desirability functions, calculated by Equation (4), where w_i is a comparative scale for weighing each of the resulting d_i assigned to the ith response, and n is the number of responses. The optimal settings are determined to maximize overall desirability (D).

$$D = \left({d_1}^{w_1} \times {d_2}^{w_2} \times {d_3}^{w_3} \times \ldots\ldots \times {d_n}^{w_n}\right)^{\frac{1}{(w_1 + w_2 + w_3 + \cdots + w_n)}} = \prod_{i-1}^{n} {d_i}^{{w_i}^{\frac{1}{\sum_{i=1}^{n} w_i}}} \qquad \ldots\ldots\ldots (4)$$

Finally an attempt has also been made to identify optimum parameters setting for single quality characteristic using Taguchi's signal to noise (S/N) ratio.

4. Results and discussions

The machining time (T_m) for each of the experiments expressed in minutes is recorded by a stopwatch while the average roughness, Ra expressed in µm is measured by Taylor Hobson 3D Surface Profilometer. The design matrix for performing the experiments along with the corresponding values of T_m and surface roughness (SR) are shown in Table 2.

Table 2: Design matrix along with machining time and surface roughness

Exp. No	T_{ON}	Toff	IP	SV	T_m (min)	SR (µm)
1	0.85	46	220	25	8.43	2.68
2	0.85	19	230	20	8.21	2.96
3	0.85	32	220	20	8.92	3.04
4	0.60	46	220	20	7.41	3.35
5	1.10	32	230	20	7.68	3.21
6	0.85	19	210	20	9.43	3.12
7	0.85	32	220	20	9.21	2.96
8	0.60	19	220	20	9.47	3.42
9	0.60	32	210	20	9.51	2.67
10	0.85	19	220	15	9.77	3.03
11	0.60	32	230	20	8.42	3.17
12	0.85	19	220	25	9.20	3.05
13	1.10	32	220	25	9.48	3.07
14	0.85	46	210	20	8.60	3.09
15	0.85	46	230	20	8.66	3.20
16	0.85	32	230	25	8.93	3.07
17	0.85	32	210	25	7.47	3.25
18	0.60	32	220	25	8.43	3.05
19	1.10	32	220	15	8.20	3.11
20	0.85	32	230	15	7.05	2.93
21	1.10	32	210	20	6.93	2.97
22	0.85	32	210	15	7.45	3.00
23	0.60	32	220	15	9.32	2.96
24	0.85	32	220	20	9.15	2.92

25	0.85	46	220	15	8.68	3.10
26	1.10	19	220	20	9.53	3.17
27	1.10	46	220	20	8.48	3.24

The individual desirability (d_i) is calculated for both the responses, viz. machining time and surface roughness depending upon type of quality characteristics. Since both the responses are possessing minimization objective, the equation corresponding to minimum target is selected. The computed individual desirability for each quality characteristics using equation 2 are shown in Table 3. The overall desirability calculated by equation 4 along with the rank is also shown in Table 3. The weightage for each response is taken as 0.5.

Table 3: Optimization using DFA

Exp. No	Individual desirability (d_i)		Overall Desirability (D)	Rank
	T_m	SR		
1	0.4718	0.9867	0.6823	3
2	0.5493	0.6133	0.5804	5
3	0.2993	0.5067	0.3894	13
4	0.8310	0.0960	0.2824	22
5	0.7359	0.2800	0.4539	8
6	0.1197	0.4000	0.2188	23
7	0.1972	0.6133	0.3478	16
8	0.1070	0.0000	0.0000	26
9	0.0915	1.0000	0.3026	21
10	0.0000	0.5200	0.0000	26
11	0.4754	0.3333	0.3981	12
12	0.2007	0.4907	0.3138	19
13	0.1021	0.4613	0.2170	24
14	0.4120	0.4467	0.4290	9
15	0.3894	0.2933	0.3380	17
16	0.2972	0.4680	0.3729	15
17	0.8099	0.2267	0.4284	10
18	0.4718	0.4893	0.4805	6
19	0.5528	0.4133	0.4780	7
20	0.9577	0.6573	0.7934	1
21	1.0000	0.6053	0.7780	2

22	0.8169	0.5600	0.6764	4
23	0.1585	0.6133	0.3117	20
24	0.2183	0.6667	0.3815	14
25	0.3838	0.4267	0.4047	11
26	0.0845	0.3333	0.1678	25
27	0.4542	0.2400	0.3302	18

From Table 3, it can be concluded that experiment number 20 having D value of 0.7934 gives the optimal input parameters setting i.e. T_{ON}: 0.85 μs, T_{OFF}: 32 μs, IP: 230A and SV: 15V.

The optimal parameters setting for each of the responses is also obtained using Taguchi's signal to noise (S/N) ratio. Taguchi's main effects plot of S/N ratios for smaller machining time and smaller SR are shown in Figure 3 and 4 respectively from which it is observed that the optimum

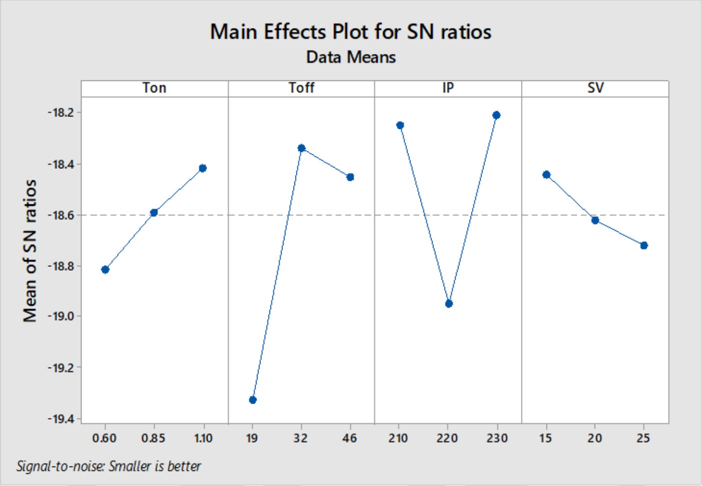

Figure 3: S/N ratio for machining time

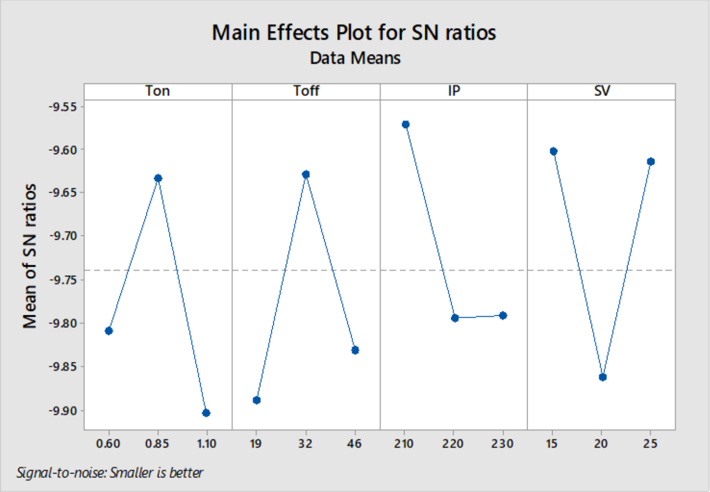

Figure 4: S/N ratio for SR

parameters setting for minimum machining time are T_{ON}: 0.60µs, T_{OFF}: 32 µs, IP: 220A and SV: 20V, while the optimum parameters setting for minimum SR are T_{ON}: 1.10 µs, T_{OFF}: 19 µs, IP: 220A and SV: 20V.

5. Conclusions

In this paper an attempt has been made to study and optimize the output responses in WEDM of Inconel 800. Four design variables, viz. T_{ON}, T_{OFF}, IP and SV respectively are selected at three levels and the design matrix for the experiments is developed on the basis of 1/3 Fractional Factorial Design with no replication thus resulting in a total of 27 numbers of experiments. The two responses of the experimentation, viz. machining time and surface roughness are optimized using DFA, a search-based optimization method which optimizes multiple response variables, individually and simultaneously, to find the optimum input variable settings. Based on the above cited technique it is observed that the maximum value of overall desirability of 0.7934 is recorded for the input parameters setting of T_{ON}: 0.85 µs, T_{OFF}: 32 µs, IP: 230A and SV: 15V and thus it may be considered as the optimal setting. Similarly, the optimal parameters setting for each of the responses is also obtained using Taguchi's signal to noise (S/N) ratio and it is observed that for minimum machining time, the input parameters are T_{ON}: 0.60µs, T_{OFF}: 32 µs, IP: 220A and SV: 20V respectively, while the optimum parameters setting for minimum SR are T_{ON}: 1.10 µs, T_{OFF}: 19 µs, IP: 220A and SV: 20V.

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