Experimental Investigations during Dry EDM of Inconel – 718

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Abstract. Dry EDM is a modification of the conventional EDM process in which the liquid dielectric is replaced by a gaseous medium. Tubular tool electrodes are used and as the tool rotates, high velocity gas is supplied through it into the discharge gap. The flow of high velocity gas into the gap facilitates removal of debris and prevents excessive heating of the tool and work piece at the discharge spots. It is now known that apart from being an environment–friendly process, other advantages of the dry EDM process are low tool wear, lower discharge gap, lower residual stresses, smaller white layer and smaller heat affected zone. Keeping literature review into consideration, in this paper, an attempt has been made by selecting compressed air as a dielectric medium, with Inconel – 718 as a work piece material and copper as a tool electrode. Experiments are performed using Taguchi DoE orthogonal array to observe and analyze the effects of different process parameters to optimize the response variables such as material removal rate (MRR), surface roughness (Ra) and tool wear rate (TWR). In the current work, a unit has been developed to implement dry EDM process on existing oil based EDM machine.

Keywords: Dry Electrical Discharge Machining (Dry EDM); Material Removal Rate (MRR); Surface roughness (Ra); Tool Wear Rate (TWR); Taguchi method, Analysis of variance.

1. Introduction

Electric Discharge Machining (EDM) is a thermal process in which material is removed by rapid and repetitive sparks generated between work piece and tool when both are submerged in dielectrics. It is most popular non-traditional machining process used for various shop floor applications. As the electrical energy and other parameters can be controlled electric discharge machining (EDM) process provides high precision and reliability. Apart from its advantages, environmental issues are associated with the process have been a major drawback of EDM [1]. Use of hydrocarbon oil based dielectric fluids in EDM process are the major sources of pollution. To make this process environment-friendly liquid dielectrics are replaced by gases.

Dry EDM is a new process in which the liquid dielectric is replaced by a gaseous as a medium. Hallow pipe tool electrodes are used and as the tool rotates, high velocity gas is supplied through it into the discharge gap. The flow of high velocity gas into the gap provides removal of debris and prevents excessive heating of the tool and work piece at the discharge spots. It is an environment–

friendly process, and apart from that it provides other advantages such as low tool wear, lower discharge gap, lower residual stresses, smaller white layer and smaller heat affected zone [5]. Dry EDM is one of the novel EDM techniques, which employs gas as a dielectric medium instead of liquid. It mainly involves supply of a gas through a rotating thin-walled pipe electrode, which also flushes out the debris from inter-electrode gap. The process holds the potential to be a viable alternative to conventional liquid dielectric EDM for precision oriented machining applications. The major advantage of this method is its simplicity.

2. Literature review

Kunieda and Yoshida [2] attempted air as a dielectric medium for EDM machining in 1996. They have used steel as a work piece, copper as tool electrode and compressed air as a dielectric. They found that the material removal rate is much higher with tool electrode as a negative polarity compared with the positive polarity. In contrast, in the case of EDM in a liquid, there is higher material removal rate when the polarity of the tool electrode is positive. They compared machining characteristics between EDM in air with a negative tool electrode and EDM in oil with a positive tool electrode. They also found that the tool electrode wear ratio is much lower when the polarity of the tool electrode is negative compared with the case in which the polarity of the tool electrode is positive. Kunieda et al. [4] have used a piezoelectric actuator to improve the dry EDM characteristics by controlling the discharge gap distance. They have used copper-tungsten pipe of 1mm in diameter as tool electrode, carbon steel as a work piece and compressed air as dielectric. They found that with increasing gain of the driver for the piezoelectric actuator, the probability of short circuiting decreases, by resulting in considerable increase of the material removal rate. They also found that tool wear ratio was 0.29%, and it took 43 minutes to machine the grooves with a depth of 0.8mm. Without the piezoelectric servo, the tool wear ratio was 1.3 times higher and the machining took 1.7 times longer. Tao et al. [8] have experimentally investigated the dry and near dry EDM process in 2008. A two phase gas-liquid mixture was used as the dielectric medium in near dry EDM. The effect of discharge current, pulse-duration, pulse interval, gap voltage and open circuit voltage was investigated at constant values of gas pressure and tool rpm by using a 2^{5-1} fractional factorial designed experiment. It was found that copper tool and oxygen gas dielectric with a high current and low pulse off time were suitable for rough machining with a high material removal rate (MRR). The highest material removal rates (MMR) of 1.8 mm^3/min have been reported using kerosene-air mixture used as dielectric. Govindan and Joshi [10] have worked on performance of dry EDM using slotted electrodes in 2011.They have used copper as tool electrode, SS304 as work piece and oxygen as dielectric medium. They tried with different slots on electrode in their experiment and reported with four slots as a effective number of slots for highest material removal rate (MMR). They have registered the highest average material removal rate (MRR) of 1.497 mm^3/min. They conclude that, the use of electrodes with peripheral slots helps flush debris particles more effectively and hence promotes improvement in material removal rate (MRR). Govindan and Joshi [9] worked on experimental characterization of material removal in dry electrical discharge drilling. They have used copper as tool electrode, steel as work piece material and oxygen as a medium. They have mentioned two phenomenon of tool wear rate (TWR) that is erosion of electrode material and deposition of material on the electrode. They have found minimum tool wear at oxygen pressure at 94.5%, radial clearance at 88.5% and spindle speed at 88%. In their experiment tool wear rate (TWR) was almost close to zero and none of the input parameter influencing tool wear rate (TWR). Grzegorz Skrabalak and Jerzy Kozak [13] carried out study on dry electrical discharge machining. They compared surface roughness during DEDM milling with single hole and 2-channel electrodes. They also presented basic characteristic of the DEDM milling process and comparison of this green machining method with kerosene based EDM milling.

Tomadi et al. [11] reported a work to study the influence of operating parameters of tungsten carbide on the machining characteristics such as surface quality, material removal rate and electrode wear. They carried out confirmation test to evaluate the error margin between predicted result by software and confirmation result by experiment in terms of the machining characteristics. They reported effectiveness of EDM process with tungsten carbide, WC-Co in terms of the material removal rate, the relative wear ratio and the surface finish quality of the work piece produced. Izquierdo et al. [14] presented a new contribution to the simulation and modelling of the EDM process. They used finite difference schema for numerical calculation of temperature fields within the work piece generated by the superposition of multiple discharges during an actual EDM operation. They estimated characteristics of the discharge such as energy transferred onto the work piece, diameter of the discharge channel and material removal efficiency by using inverse identification from the results of the numerical model. The model has been validated through industrial EDM tests, showing that it can efficiently predict surface roughness with errors below 6%. Pichai et al. [15] attempted experiments to study the effect of a copper-graphite electrode (EDM-C3) material on tungsten carbide work piece during the electrical discharge machining process. They found that the important parameters for this process are the discharge current, the on time, the off time, the open circuit voltage and the electrode polarity. They observed significant improvement in the surface roughness (Ra) with negative polarity electrode. They evaluated effectiveness of the process by the surface roughness Ra (μm) which is determined by scanning electron microscopy (SEM).

The literature review above indicates that most of the researchers have investigated influence of a limited number of process parameters on the performance measures of dry EDM process. Also the influence of machining parameters on Inconel-718 has not been fully explored using dry EDM machining with copper as electrode. As Inconel-718 (nickel-based super alloy) is a high strength, temperature resistant (HSTR) material which is extensively used in aerospace applications, such as gas turbine, rocket motors, and spacecraft as well as in nuclear reactors, pumps and tooling. The analysis of effect of different machining parameters on Inconel-718 is thus very essential. Hence in this paper attempts are made to see the effect of various process parameters on Inconel-718 with dry EDM.

3. Experimental setup and procedure

3.1 Design of Experiment based on Taguchi Method:

In Taguchi method, process parameters which influence the products are separated into two main groups: control parameters and noise parameters. The control parameters are used to select the best conditions for stability in design or manufacturing process, whereas the noise parameters denote all parameters that cause variation [16]. According to Taguchi based methodology, the characteristic that the larger value indicates better machining performance, such as material removal rate (MRR) is addressed as the-larger-the-better type problem and smaller value indicates the better machining performance, such as tool wear rate (TWR), surface roughness Ra(μm) are addressed as smaller the better type problem.

The experiments were performed on CNC EDM machine (S-50 model) of Electronica Machine Tools Ltd. with Inconel 718 as a work piece material (166 x 160 x 3 mm), copper hollow electrode (Outer diameter = 7.5 mm, Inner diameter = 4.5 mm) and compressed air as dielectric media. Table 1 shows different parameters with their levels used in experiments and table 2 shows L9 orthogonal array with experimental parameters. Figure 1 shows the setup of machining zone.

Table 1. Process parameters with their levels

Sr No.	Parameter	Levels I	Levels II	Levels III
1	Current, IP (Amp)	10	13	16
2	Pulse on time, Ton (μs)	50	100	150
3	Gas Pressure, GP (Kgf/cm^2)	1	2	3

Table 2. L_9 orthogonal array with experimental parameters

Exp. No.	Current (IP) (Amp)	Pulse on time (Ton) (µs)	Gas Pressure (GP) (Kgf/cm^2)
1	10	50	1
2	13	50	2
3	16	50	3
4	10	100	2
5	13	100	3
6	16	100	1
7	10	150	3
8	13	150	1
9	16	150	2

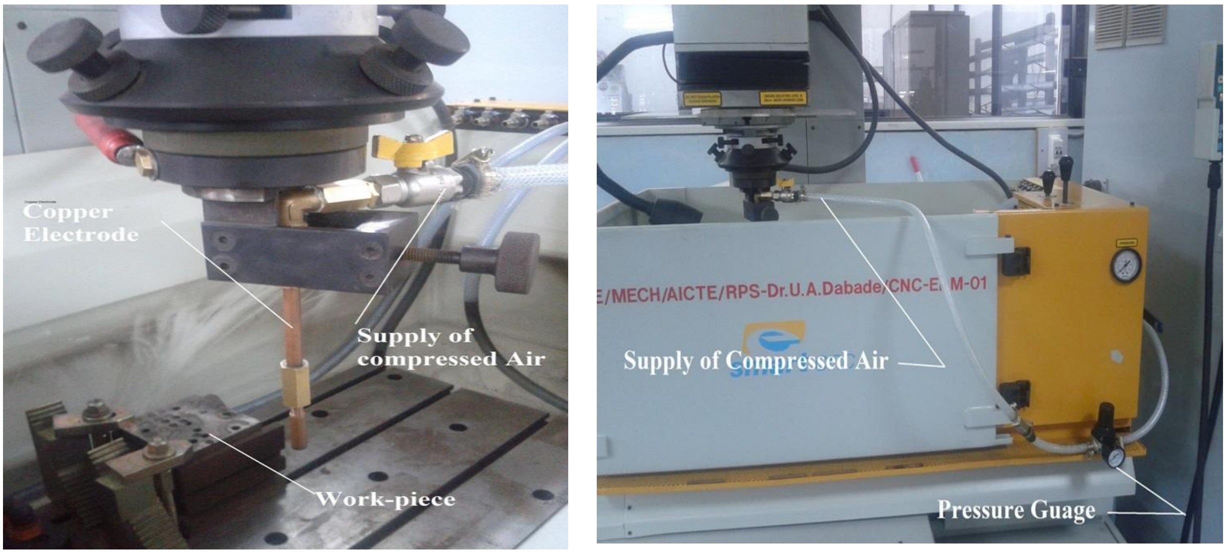

Figure 1. Experimental set-up

3.2 Response Variables:
In this study, the evaluation of various response variables is performed as discussed below,
Material removal rate (*MRR*) is calculated using equation

$$MRR = \frac{\frac{\Pi}{3} * h * (R^2 + r^2 + R * r)}{t} \qquad \text{(i)}$$

Where, *R*= EDMed hole radius at top side, *r* = EDMed hole radius at bottom side, *h*= Work piece thickness and *t* = Machining time
The tool wear rate (*TWR*) was measured using the weight difference before and after machining using equation (ii),

$$TWR = \frac{Wb - Wa}{t} \qquad \text{(ii)}$$

Where W_b=Weight before machining and W_a= Weight after machining
Mitutoyo surface test is used to measure the average arithmetic surface roughness (*Ra*) in µm.

4. Results, analysis and discussion

The statistical software, Minitab 16 was used and the results obtained for all the experimental runs were statistically analyzed using analysis of variance (ANOVA) at 95% confidence level and the effects of the selected variable were evaluated. In this work, nine experiments based on Taguchi (L9) experimental design methodology were conducted and results were shown in table 3 for material removal rate (MRR), tool wear rate (TWR) and surface roughness Ra(µm).

Table 3. F and P values of ANOVA for response variables

Source	DF	MRR (mm^3/min)		TWR (gm/min)		Ra (µm)	
		F	P	F	P	F	P
POT	2	13.04	0.071	57.75	0.017	8.93	0.101
CURRENT	2	9.16	0.098	113.33	0.009	2.08	0.325
GP	2	0.02	0.976	2.45	0.290	4.99	0.167
Error	2						
Total	8						
		R-Sq=95.69% R-Sq(adj)=82.77%		R-Sq=99.43% R-Sq(adj)=97.71%		R-Sq=94.12% R-Sq(adj) = 76.48%	

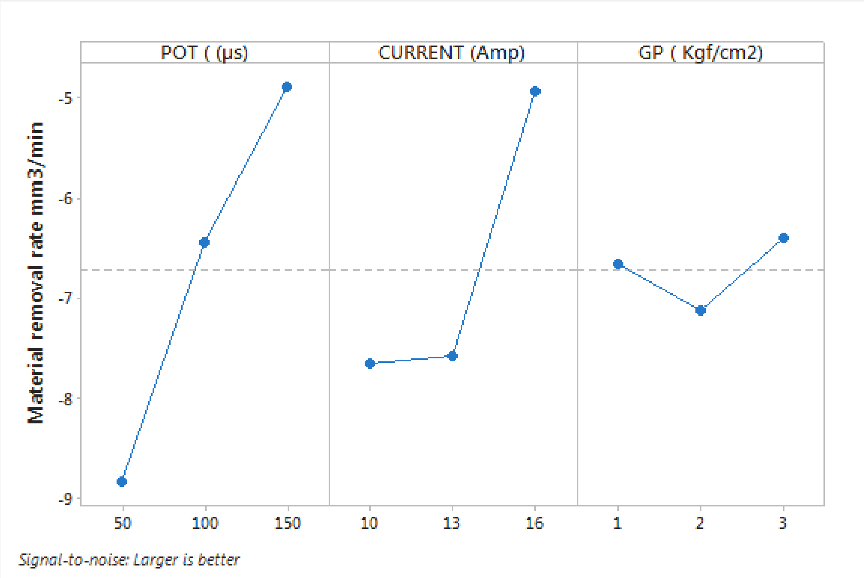

Figure 2. Main effects plot for SN ratios of MRR

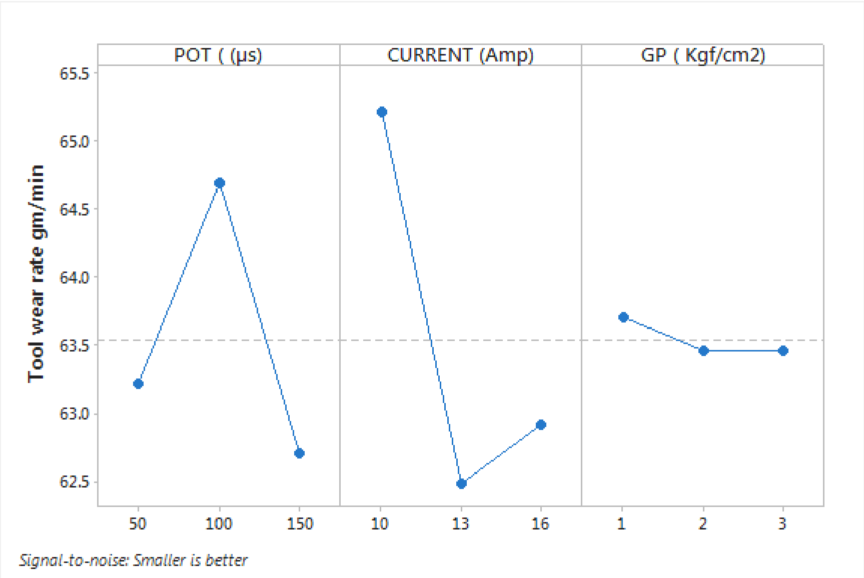

Figure 3. Main effects plot for SN ratios of TWR

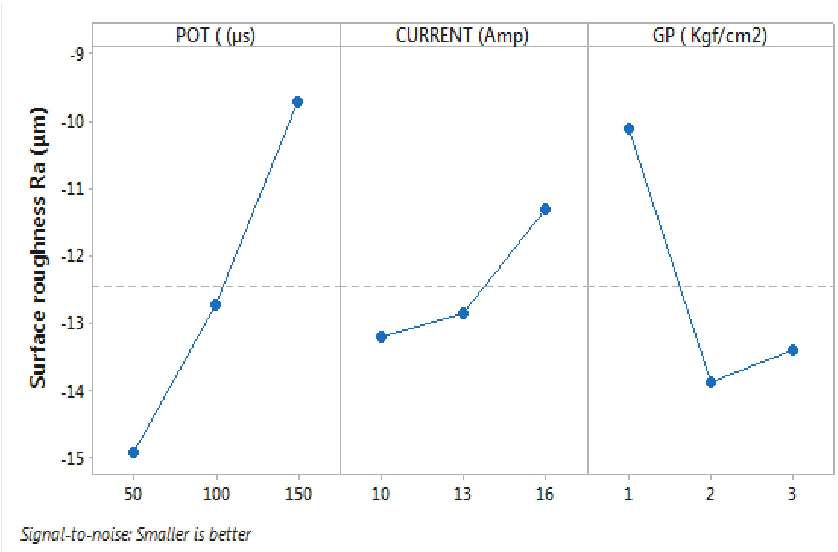

Figure 4. Main effects plot for SN ratios of Ra(μm)

ANOVA for material removal rate (MRR) (ref. table 3) indicates that pulse on time (POT) as the most significant factor followed by current whereas gas pressure results into non significant parameter. Figure 2 shows that as pulse on time and current increases, material removal rate (MRR) increases. This is because the number of electrons striking the work surface in a single discharge increases thus eroding out more material from the work surface per discharge.

ANOVA for tool wear rate (TWR) (ref. table 3) indicates that Current (I) as the most significant parameter followed by pulse on time (POT) whereas gas pressure results into non significant parameter. Figure 3 shows as the pulse on time (POT) increases from 50 μsec to 100 μsec the number of electrons striking in single discharge on the material surface increases which in turn erodes the tool material and when the pulse on time (POT) increases from 100 μsec to150 μsec the eroded material get attached to the tool material which in turn reduces the tool wear rate. As the current increases from 10 amp to 13 amp the maximum amount of discharge energy is used to remove material from work piece which deposits eroded material on the tool so it decreases the tool wear rate (TWR) and for 13 amp to 16 amp the electrons striking increases which removes deposited particles and try to remove maximum amount of work piece material which in turn increases the tool wear rate (TWR).

ANOVA for surface roughness Ra (μm) (ref. table 3) indicates that pulse on time (POT) as the most significant parameter followed by gas pressure whereas current results into non significant parameter. Figure 4 shows that as pulse-on time increases, the discharge energy increases causing formation of larger crater diameter and depth which results into increment in surface roughness Ra (μm).As gas pressure acts as a coolant, at initial stage from 1 Kgf/cm^2 to 2 Kgf/cm^2, it tries to improve the surface roughness Ra (μm), but as it increases from 2 Kgf/cm^2 to 3 Kgf/cm^2, it causes removal of more amount of debries from the material surface causing increment in surface roughness Ra (μm) value.

5. Conclusions

In this study, the effect of process parameters on the response variables (MRR, TWR, surface roughness) of Inconel 718 was investigated experimentally in Dry EDM.

- For material removal rate (MRR) pulse on time (POT) was found to be most significant factor followed by current (I) and for this work maximum material removal rate (MRR) reported is 0.7061 mm^3/min.
- For tool wear rate (TWR) current (I) was found to be most significant factor followed by pulse on time (POT) and the minimum tool wear rate (TWR) obtained is 0.000471976 gm/min.
- For surface roughness Ra (μm) pulse on time (POT) was found to be most significant factor followed by gas pressure (GP) and the minimum surface roughness Ra (μm) obtained is 2.169.

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