Optimization of machining parameters in dry EDM of EN31 steel

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Abstract. Dry electric discharge machining (Dry EDM) is one of the novel EDM technology in which gases namely helium, argon, oxygen, nitrogen etc. are used as a dielectric medium at high pressure instead of oil based liquid dielectric. The present study investigates dry electric discharge machining (with rotary tool) of EN-31 steel to achieve lower tool wear rate (TWR) and better surface roughness (Ra) by performing a set of exploratory experiments with oxygen gas as dielectric. The effect of polarity, discharge current, gas flow pressure, pulse-on time, R.P.M. and gap voltage on the MRR, TWR and surface roughness (Ra) in dry EDM was studied with copper as rotary tool. The significant factors affecting MRR are discharge current and pulse on time. The significant factors affecting TWR are gas flow pressure, pulse on time and R.P.M. TWR was found close to zero in most of the experiments. The significant factors affecting Ra are pulse on time, gas flow pressure and R.P.M. It was found that polarity has nearly zero effect on all the three output variables.

1. Introduction

Electric discharge machining (EDM) is one of the most important machining process in manufacturing industries. EDM is a ‘non-conventional manufacturing method’, which has been accepted worldwide in late 1940’s. Electric discharge machining is a thermo electric machining process in which energy in the form of heat (electric spark) is used to remove unwanted material from work piece through localized melting and vaporization process. When the electric power in short pulses is supplied, an electric spark is produced between the work piece and tool electrode. The sparking frequency may be thousands of sparks per second. The temperature of this area is very high due to the spark developed between the work piece and electrode which can partly melt and vaporize material from both electrodes. Most of the eroded material is washed away between tool and work piece gap in form of debris by dielectric fluid. Electric power is supplied in short pulses is supplied to prevent excessive heating. Sparks occur at various locations between tool and work piece surface whenever there occurs a small gap between tool electrode and work piece surface. Uniform gap distance is formed throughout the gap between the tool and the work piece due to material removal. Thus, a mirror image of the tool is generated on the work piece surface as shown in figure 1.

Figure 1. Tool and work piece during EDM operation.
Dielectric fluid plays very important role in material removal in EDM machining. It localizes the spark into small cross-sectional, cools the electrodes and flushes away the sludge from the machining zone. Generated surface are influenced by type, quality and flushing arrangement of the dielectric.

Dry Electric Discharge Machining (EDM) is a novel EDM technique in which a gas is used as a dielectric medium. Dry electric discharge machining is the modified concept based on oil EDM process in which gaseous dielectric like helium, argon, oxygen, nitrogen and air etc. is used instead of liquid dielectric. Dry electric discharge machining is an eco-friendly EDM technique because of absence of waste and emission of liquid dielectrics. In dry electric discharge machining, a high velocity gas jet from a pipe tool electrode reacts with the work piece material under high temperature caused by arc discharge and enhances the evaporation and melting of the work piece at the discharge spot. The high velocity gas flow between the gap protect over heating of work piece and tool which also remove debris and also protect reattachment to machined surface and tool electrode.

Dry electric discharge machining is done for obtaining less tool wear, smaller gap discharge, smaller residual stresses, and lower heat affected zone. Figure 2 shows the schematic diagram of dry EDM process.

![Figure 2. Schematic diagram of dry EDM process [1]](image)

In dry EDM, gas having high velocity flows through tubular electrode which acts as dielectric medium for the process. During the process, debris particles are carried away by the continuous flow of gas between work piece and tool electrode and also cools the tool and work piece.

**Literature review and problem formulation**

In 1970’s, the English scientist, first detected the erosion effects of electric sparks on various metals. It was very imprecise and riddled with failures. But, by electric spark, metal erosion was not taken into account until 1943 when a Russian scientist could learnt how erosion of the metal control the machining. In the mid 1980’s, the electric discharge machining techniques were adapted to machine tool. A paper from NASA in 1985 reported that a “dry Electrical Discharge Machining Process” is possible if inert gas (helium or argon) is used as dielectric medium for drilling with use of tubular electrode.

In 2004, Kunieda et al. studied the improvement in dry electric discharge machining statistics with piezoelectric actuator used for controlling gap length in tool steel material. An EDM performance simulator was developed to conclude the effects of piezoelectric actuator on MRR and machining stability of dry EDM taking copper-tungsten tube as tool and high velocity oxygen gas as the dielectric [2]. Li et al. (2006) investigated on the of electrode materials that effected machining performances of electrical discharge machining (EDM) [3]. Kao et al. (2007) studied that to achieve mirror like surface finish, near dry electric discharge machining process is used for finishing process [4]. Joshi et al. (2011) investigated for improving process performance, the dry electric discharge machining process was performed in pulsating magnetic field [5]. A comparison of dry-EDM and conventional EDM for machining micro holes in Si3N4-TiN ceramic was carried out by Uhlmann et al. (2016) [6]. The results from the study showed that dry-EDM has higher effective pulse frequency and shorter relative motions between workpiece and tool electrode. Shen et al. (2016) conducted milling experiments on Ti6Al4V by high-speed near dry-EDM process using mist as a dry dielectric. The effect of current, pressure, rotation speed, droplet size and droplet density on MRR, surface roughness were studied [7].
It was observed from literature survey that it is possible to machine EDM in high velocity gaseous flow through the rotary tool electrode. It was also observed that research work related to Dry EDM is insufficient in the field of process parameters and optimization of dry EDM. However many research works for the conventional EDM machining on EN31 steel was studied in the field of process parameters and optimization. So there is need to investigate dry EDM (an environmental friendly EDM technology) to maintain environmental harmony for future generation.

The present work was carried out to achieve following objectives:

a) To develop a rotary dry EDM setup on an existing EDM machine.
b) To determine the effect of machining factors on response variables using oxygen as dielectric medium, copper as rotary tool and EN31 steel as the work piece.

2. Experimentation

Experiments were planned to study the effect of different operating parameters on the Material removal rate (MRR), Tool wear rate (TWR) and Surface finish (Ra) in rotary tool dry EDM. Operating parameters namely Polarity, Discharge current (I_d), Gas Flow Pressure, RPM, Pulse-on time (T_on) and Gap voltage (V_g); were decided for experiment. Taguchi design based L-32 orthogonal array was used in experiment work in which total of 32 run were carried out to determine the effective operating parameters on Dry EDM.

2.1 Electric Discharge Machine

All the experiments were conducted on Electric Discharge Machine, Savita-Economy (die-sinking type). The EDM Machine is Micro Controller based EDM. The servo control mechanism is based on gap distance between the tool electrode and work piece. During machining, the rotary tool is fed onto work piece for maintaining constant gap distance. The servo control feedback is based on the inter electrode gap (IEG) between the tool and the work piece which is determined by the gap voltage. In this machine, the inter electrode gap (IEG) cannot be controlled independently. The dielectric fluid, which can be in the form of gas, is delivered through a tubular rotary tool electrode is delivered through jet flushing.

For enabling the performance of dry EDM machining (rotary tool) on existing EDM machines (which were originally designed for liquid dielectric only), a dry EDM with rotary tool has been designed and developed. High pressure oxygen gas is supplied from the oxygen cylinder through gas supply hose. For oxygen supply, 250 kgf/cm² oxygen cylinders were used. At the inlet to the EDM machine, a
maximum gauge pressure of 4 kgf/cm\(^2\) was available. A Bourdon tube pressure gauge with a least count of 0.1 kgf/cm\(^2\) is used to monitor the inlet pressure to the dry EDM unit.

2.2 Workpiece and tool electrode
EN31 is a high carbon Alloy steel which achieves a high degree of hardness with compressive strength and abrasion resistance. Experiment were conducted by choosing EN31 steel material as work piece and copper electrode as electrode in the form of single tube tool with central hole for supplying high velocity gas. The tool electrode is in the form of circular cylinder of 10 mm diameter with central hole of diameter 3 mm. Specifications of work piece and tool electrode shown in Table 1. The application for EN31 material is not only for forgings, castings, axles, shafts, cranks and connecting rods but also as a low cost die material in tool and die-making industries [8]. The experiments were conducted for 10 minutes and weight of tool and work piece before machining was noted.

### Table 1. Specifications of workpiece and tool electrode.

|                  | Work piece                          | Tool      |
|------------------|-------------------------------------|-----------|
| Material         | EN-31 Steel (Euro-Norm - 31 Steel) | Copper    |
| Composition      | C - 1.5%, Si – 0.22%, Mn – 0.52%, Cr – 1.3%, S – 0.05%, P - 0.05% | ---       |
| Hardness         | 63HRC                               | 40 BHN    |
| Tensile Strength | 750 N/mm\(^2\)                      | 240 MPa   |
| Density          | 7.8 g/cm\(^3\)                      | 8.90 g/cm\(^3\) |
| Modulus of elasticity | 215 000 N/mm\(^2\)            | 110000 N/mm\(^2\) |
| Melting Point    | 1370\(^\circ\)C                     | 1083\(^\circ\)C |

3. Results

3.1 Material removal rate (MRR)
During the process of Dry EDM, the influence of various machining parameter like polarity, discharge current, gas flow pressure, pulse on time, R.P.M., and gap voltage on MRR are shown as main effects plot for signal to noise ratios of MRR (Larger is better) in figure 4.

![Figure 4. Main effects plot for SN ratios (MRR).](image)

The discharge current (Ip) depends directly upon MRR ranging from 12A to 24A. This is expected as discharge current increases directly produces stronger spark, which results in rise of temperature, resulting more unwanted material eroded. The data signifies that no factor other than that influences
the process. As the value of Id increases from 12A to 24A, MRR also increases. Straight polarity is more significant for MRR from reverse polarity. Increase in gas flow pressure increases MRR and decreases due to low stability by high gas pressure (Kuneida et al., 1991). Increase in duty factor monotonically increase then decrease the MRR value. Same trend is for the gap voltage.

3.2 Tool wear rate (TWR)
During the process of Dry EDM, the effect of machining parameters like polarity, discharge current, gas flow pressure, R.P.M., pulse on time and gap voltage on TWR is shown in main effects plot for S/N ratios of TWR (Smaller is better) in figure 5. It is clearly shown that increase in gas flow pressure decreases the TWR in the range of 1.5kgf/cm² to 2.5kgf/cm² monotonically increases upto 3.0kgf/cm². This is expected with increase in gas flow pressure, cooling effect to the tool also increases. Besides, it is clear from the figure 5 that with increase in the value of discharge current and R.P.M., TWR decreases.

![Main Effects Plot for SN ratios (TWR)](image)

**Figure 5.** Main effect plots for SN ratios (TWR).

The factor which affects most significantly the tool life in machining EN31 by dry EDM (rotary tool), are the gas flow pressure, R.P.M. and pulse on time; therefore the TWR can be controlled by selecting a suitable gas flow pressure, R.P.M. and pulse on time values. However, the tool wear rate is very small nearly zero in the dry EDM.

3.3 Surface roughness (Ra)
During the process of Dry EDM, the influence of various machining parameter like polarity, discharge current, gas flow pressure, R.P.M., pulse on time and gap voltage on Ra is shown as main effect plot for S/N ratios for surface roughness (Ra) (Smaller is better) in figure 6.
It is clearly shown that increase in pulse on time drastically decreases the Ra in the range of 175μs to 200μs. Increase in gas flow pressure decreases the Ra. But, as the discharge current increases from 12A to 20A, increases Ra. It shows that reverse polarity is more effective for Ra than straight polarity. The contribution of the pulse on time, gas flow pressure and discharge current are 29.64%, 19.25% and 17.06% respectively.

3.4 Summary of results
From the analysis of responses following summary table for all control factors is prepared for the SN ratios as in Table 2.

Table 2. Summary of responses.

| Rank | Response | Polarity | Discharge Current | Gas Flow Pressure | RPM | Pulse On Time | Gap Voltage |
|------|----------|----------|-------------------|-------------------|-----|---------------|-------------|
| MRR  | 6        | 1        | 4                 | 3                 | 2   | 5             |
| TWR  | 6        | 4        | 1                 | 2                 | 3   | 5             |
| Ra   | 6        | 3        | 2                 | 5                 | 1   | 4             |

| % of Contribution | MRR | TWR | Ra   |
|-------------------|-----|-----|------|
| MRR               | 3.76| 22.36| 15.64|
| TWR               | 3.99| 15.95| 20.89|
| Ra                | 2.56| 17.06| 19.25|

4. Conclusions
In present study, machining effects of parameters on MRR, TWR and Ra of EN31 steel work piece having rotary tool electrode having flushing through tool were investigated for Dry-EDM process. From the analysis of the results, following conclusions can be drawn:
- It was found that dry EDM (Rotary Tool) process is feasible by using oxygen gas with the injecting flushing of dielectric gas.
- The significant factors for MRR are discharge current (P=0.015), Pulse on time (P=0.027) and R.P.M. (P=0.031).
- The significant factors for TWR are gas flow pressure (P=0.011), R.P.M. (P=0.013) and Pulse on time (P=0.016).
- The significant factors for Ra are Pulse on time (P=0.004), gas flow pressure (P=0.017) and discharge current (0.019).
- The highest % of contribution for MRR, TWR and Ra are discharge current (22.36%), gas flow pressure (20.89%) and Pulse on time (29.64%).
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