Multi-objective optimization of material removal rate and surface roughness in electrical discharge turning of titanium alloy (Ti-6Al-4V)

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Electrical discharge turning (EDT) is a unique form of electrical discharge machining (EDM) process, which is being especially developed to generate cylindrical forms and helical profiles on difficult to machine materials at both macro and micro levels. This study presents an experimental investigation of electrical discharge turning of titanium Ti-6Al-4V alloy. The objective is to investigate the influence of machining parameters including polarity, pulse-on time, peak current, gap voltage and spindle speed on performance characteristics. Taguchi-grey relational approach based on multi objective optimization has been used to maximize material removal and to minimize surface roughness. It has been found that polarity followed by peak current has most influential nature in EDT process. The confirmation experiment shows an improvement in material removal rate of 12.70% and surface roughness of 5.57% through this approach.

Keywords: Electric discharge machining (EDM), Electrical discharge turning (EDT), Material removal rate (MRR), Surface roughness ($R_a$), Taguchi-Grey relational analysis

Titanium (Ti) is the fourth most abundant metal element available in the earth's crust after aluminium, iron and magnesium. The usage of titanium and its alloy is increasing in many industrial and commercial applications due to its excellent metallurgical, physical, and mechanical properties such as; high strength to weight ratio, good corrosion resistance, high temperature stability and biological compatibility. These properties make them suitable for wide range of applications, such as biomedical applications, aerospace and automobile industry. The most common titanium alloy is the α+β type two phase Ti-6Al-4V alloy. Because of its low thermal conductivity, high strength at elevated temperature and chemically reactive nature, traditional machining techniques are often unable to machine the alloy economically. Hence, it is classified as a difficult-to-cut material. Electrical discharge machining (EDM) is a better alternative or sometimes the only alternative in generating accurate 3-D complex shaped features and components of this difficult-to-machine material. EDM is an energy based technique extensively used in machining hard and fragile materials to make die and moulds. This machining method uses a series of discrete electrical sparks between a tool electrode and a work-piece immersed in a dielectric fluid and subjected to an electric voltage. Literally thousands of high temperature electrical discharges per second are generated and each electrical discharge produces a tiny crater by melting and vaporization, thus work material is removed and desired shape of the tool is produced into the work-piece. The key advantage of EDM is that, tool and work-piece do not come into contact, thus eliminating mechanical stresses chatters and vibration problem without mechanical deformation.

In order to increases EDM process adaptability and improvement of machining performance some additional attachments (external axis) were linked to the process. Coupling of conventional turning with EDM leads to an increase in process stability and improvement of machining efficiency. Electrical discharge turning (EDT) is an emerging area of research, developed to generate cylindrical forms on difficult-to-machine materials. The concept of EDT process is depicted in Fig. 1. Electrical discharge turning is an articulation of conventional EDM machine and a rotating spindle (axis) operates as a work holding device. In EDT process the geometry of the tool is reproduced on the rotary work-piece. A conductive strip of copper serving as a forming tool is feed against the rotating work-piece using servo
mechanism. Thus, the profile of the tool is transferred to the circumference of the rotating work-piece. This process variant has been used mainly for the electrical discharge dressing of pin and disc electrodes, that can be used as a tool for 3D micro EDM application. One of the main industrial applications of die sinking EDM machine is especially in turning aerospace honey-comb seals where internal and external seals are machined to a bur free finish with internal and external diameters from 300 mm-1400 mm. Example of a machined part using EDT method is shown in Fig. 2.

The selection of optimum cutting parameters in EDT is an important step for achieving desired quality of the electrical discharge turned component. Since the development of this process, several researchers have studied the characteristics of the EDT process considering various input and output parameters. Soni and Chakraverty conducted a comparative study of output performance characteristics between stationary and rotary tool electrode. Their findings show improvement in material removal due to better flushing action and sparking efficiency in rotary EDM of titanium. However, this result in high surface roughness. Chow et al. used disc type rotary tool in a modified conventional electro discharge machine for micro slitting of work-piece. They reported that rotary motion of tool electrode increases material removal rate and decreases thickness of recast layer. Scattergood et al. worked on development of cylindrical wire electrical discharge machining (CWEDM) process to fabricate cylindrical parts of high strength materials. Based on the obtained findings they conclude maximum MRR for CWEDM was higher than that in 2D wire EDM for same machining condition and work material. Guu and Hocheng reported about the machinability of rotating cylindrical work-piece of AISI D2 tool steel using copper electrode. Experimental results indicate that centrifugal force due to work-piece rotary motion enhances dielectric flow and improves gap flushing; thus, material removal rate increases up to two times that of conventional EDM. In addition surface roughness improves with increase in work-piece rotation. Yan et al. demonstrated a new magnetic abrasion finishing technique for improving the quality of work-piece. Experimental results show that the introduction of vibrations on rotating SKD11 tool steel work-piece reduces micro cracks and recast layer, thus improves surface quality. Matooria et al. established optimum process condition for electrical discharge turning process. They adopted Taguchi design method to study the influence of process parameters namely, voltage, power, pulse-on time, spindle speed and servo upon MRR while machining high speed steel. Based on experimental findings, power and spindle speed were found most significant factors, that is by increasing the value of these two parameters MRR increases significantly. However pulse-on time and servo have significant and reciprocal effect on it. Haddad et al. proposed Taguchi’s robust design methodology for the optimization of cylindrical wire electrical discharge turning (CWEDT) process. Krishnan and Samuel optimized MRR and $R_a$ in wire electrical discharge turning (WEDT) process using multi objective optimization method based on non-dominated sorting genetic algorithm (NSGA-II) in WEDT. Song et al. developed a novel strip EDM turning process which performs the same function as wire in wire electric discharge turning. Experimental results indicate that strip EDM produces nearly 74% more MRR than wire electrical discharge turning. In addition, the machined surface was found cusp free and nearly four times smoother than WEDM turned surface. Recently,
Giridharan and Samuel performed an experimental work to study the significance of discharge energy on the performance measures namely MRR and $R_e$ in WEDT process. The results of investigation show that, MRR increases with increase in discharge energy up to an appropriate level and then decreases. At lower discharge energy $R_e$ increases with increase in discharge energy. However at higher discharge energy $R_e$ reduces. On the other hand thickness of recast layer increases with increase in discharge energy\(^\text{16}\). Recently, Gohil and Puri\(^\text{17}\) conducted an experimental investigation on EDM turning of titanium alloy. The experimental results shows that peak current, Ton and voltage are most dominating parameters which affect MRR. With respect to $R_e$ peak current and Ton show direct proportion to it. That is $R_e$ increases as the value of these parameters increases\(^\text{17}\). Same researchers\(^\text{18}\) performed another experimental investigation to study surface integrity of EDM turned part. Experimental results indicate that peak current and pulse-on time both the parameters has most significant effect on surface roughness and shows direct proportion to it. Whereas duty factor shows inverse relation to $R_e$ as it increases $R_e$ decreases\(^\text{18}\).

Multi-objective optimization has been done extensively to optimize the EDM process. Literatures on the EDM turning of titanium (Ti-6Al-4V) are scarce in general and investigations on the characteristics of EDT in particular. Grey relational was found to be an effective technique for Multi-objective optimization problems in EDM. Lin et al\(^\text{19}\) reported the use of grey relational analysis based on the orthogonal array and fuzzy based Taguchi method for optimizing multi response EDM process. Experimental findings showed grey relational analysis is more straightforward than the fuzzy based Taguchi method for optimizing the EDM process with multiple process responses\(^\text{19\,19}\). Kao et al\(^\text{20}\) carried out electrical discharge machining parameter optimization of Ti-6Al-4V alloy using GRA for multiple performance characteristics. Electrode wear rate (EWR), MRR and $R_e$ are the response parameters considered to be optimized and input parameters pulse-on time (Ton), peak current (IP), bi pulse current (IB), and flushing pressure (FP) are selected for study. Research findings showed the considerable improvement in MRR is 12%, $R_e$ 19% and tool wear ratio 15%\(^\text{20}\). Jung and Kwon\(^\text{21}\) employed Taguchi method and grey relational approach to optimize multiple performance characteristics in micro hole drilling. Muthuramlingam and Mohan\(^\text{22}\) have carried out an experimental study of EDM parameters on multi response optimization using Taguchi grey relational analysis. Recently, Lin et al\(^\text{23}\) studied a multi response optimization method using grey-Taguchi approach for micro EDM of Ti-6Al-4V alloy.

The EDT process has a very strong stochastic nature due to the complex discharge mechanisms making it difficult to optimize machining parameters with high MRR and fine surface finish. In practice these performance parameters are conflicting in nature; because different machining parameters influence them differently. Hence, there is a need for multi response optimization to arrive at the solution to this problem. Taguchi-grey relational analysis approach is observed to be a good tool for solving multi-objective optimization in EDM process to determine the optimal solution. These methods transform multi objective problem into single objective for solving the complicated interrelationships among the multiple performing characteristics in order to optimize the machining parameters simultaneously.

In the present work, Taguchi-grey relational multi level optimization approach has been used to obtain optimal combination of process parameters for EDT of titanium alloy. MRR and surface roughness have been considered as output characteristics for optimization.

**Experimental Procedure**

The proposed EDT system comprises major subsystems: power supply, EDT tool and drives, work holding turning spindle, L-section frame and acrylic casing. The power supply comprises of a DC motor and a speed control drive. Speed of the motor is controlled with a regulated power supply. However, the speed range can be further increased by changing the size of the pulley. Spindle shaft is first press fit inside the bearings. A nylon seal was used on each side of the ball bearing to prevent debris particles entering the bearing housing. The work holding collet (ER-16, 10 mm size) is mounted at one end and a pulley is connected to the other end. Both spindle shaft and motor shaft are connected by a timing belt and two aluminium pulleys. The turning spindle assembly is fixed on the horizontal base of the L-section. The DC motor is mounted on the base of another L-section. Both the sections are connected by nut and bolts, in such a way it forms Z-section. The whole assembly is covered with a casing made of acrylic sheets to protect from flushing. The
Experimental setup for conducting experiments is shown in Fig. 3.

Experimental design
The work-piece material used in this study was a commercial bar of titanium alloy. The sample of titanium alloy that were used in the experiments were prepared in 10 mm dia. × 75 mm length. The tool electrode were made of copper and manufactured on CNC vertical machining centre in 8 mm dia. × 25 mm width × 40 mm length dimensions as shown in Fig. 4. Industrial grade EDM oil has been employed as a dielectric and used at a constant flushing pressure of 0.5 kg/cm². However, machining length and machining time was kept 25 mm and 20 min, respectively. The experiments were performed on a conventional die sinking EDM machine (500×300 ZNC; Electronica make).

Peak current, gap voltage, pulse on-time, spindle rotation speed each at three levels and polarity at two level are selected as a factor (variable parameters) which vary during the experiments according to the design of experiment. Non-variable parameters are set apart from the experiment, and they are neither presumed to have important effect on the process. In this research only the main effect of factors are of interest and their interaction are excluded from the data analysis.

In this research, Taguchi orthogonal array $L_{18} (2^3 \times 3^7)$ was adopted for design of experiments. The procedure of adoption is to find a standard array in which its number of rows is at least one more than the number of degree of freedom. Thus 18 experiments were conducted at parameter levels shown in Table 1. Each run is replicated three times, so that the total number of runs is 54. Table 2 shows the assigned orthogonal $L_{18}$ array along with the data acquired for material removal and surface roughness. Note that the experiments were run in random order. The average surface roughness ($R_a$) was measured using surface roughness tester (SV 514, Mitutoyo make) with 0.8 mm cut-off length (according to DIN EN ISO 3274:1998). The surface roughness was measured at three different sections and average of three values is considered. In order to establish the material removal rate (MRR) the weight of the work-piece were measured before and after machining using a precision self calibrating digital balance (AND, GR-200 e = 1mg.). The material removal rate was specified using the following equation:

$$MRR (mg/min.) = \frac{W_i - W_f}{t} \times 1000 \quad \cdots (1)$$

Where, $W_i$ and $W_f$ are the weights of specimen before and after machining (g) respectively, and $t$ is the machining time (min).

Taguchi method
Taguchi method is a systematic and efficacy approach to find optimal combination of input parameters. This quality analysis toll analyzes the obtained results by using signal-to-noise S/N ratio. The categories of this ratio are larger the better (LB), nominal the better (NB) and smaller the better (SB). In the present study LB has been applied for MRR whereas the SB has been applied for $R_a$.

<table>
<thead>
<tr>
<th>Table 1 — Machining parameters and their levels</th>
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<tbody>
<tr>
<td>Parameter</td>
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<tr>
<td>Polarity</td>
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<tr>
<td>Ton (µs)</td>
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<tr>
<td>Peak current (A)</td>
</tr>
<tr>
<td>Gap voltage (V)</td>
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<tr>
<td>Spindle speed (RPM)</td>
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\[ SB \eta = -10 \log \left[ \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right] \] ... (2)

\[ LB \eta = -10 \log \left[ \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right] \] ... (3)

Where, \( \eta \) denotes the S/N ratio calculated from the observed values (units: dB), \( y_i \) represents response value of the \( i^{th} \) experiment and \( n \) is the number of replications of each experiment. The logic behind S/N ratio analysis is to find a setting of parameters in which signals are predominant. This rationale eventually leads to a situation in which the system is least sensitive to noises\(^{24} \). Table 3 shows the S/N ratios of obtained response from each experiment.

Grey relational approach

In the grey relational analysis, data preprocessing is first performed in order to normalize the raw data for the analysis\(^{25} \). Generally, three different kinds of data normalizations are carried out to render the data, whether the lower is better (LB), the higher is better (HB) or nominal the best (NB). For characteristics such as MRR, the original sequence can be normalized as higher the better (HB). However, if the expectancy is the as small as possible for characteristics such as surface roughness, then the original sequence should be normalized as LB:

\[ \Delta 0_i(k) = \left| x_0^*(k) - x_i^*(k) \right| \] ... (6)

After normalizing the data and determining deviation sequences, usually grey relational coefficient is calculated to display the relationship between the optimal and actual normalized experimental results. The grey relational coefficient and grey relational grade can be expressed as Eqs (7) and (8), respectively. The grey relational grade is an average sum of the grey relational coefficients. The higher grey grade indicates closer to the optimal response in the process. Based on the Eqs (7) and (8)
the complicated multiple performance characteristics can be converted into single grey relational grade as shown in Table 3.

\[ \gamma_i(k) = \gamma(x_0(k), x_i(k)) = \frac{\Delta \min + \zeta \Delta \max}{\Delta_{0j}(k) + \zeta \Delta \max} \quad \ldots (7) \]

\[ 0 < \gamma(x_0(k), x_i(k)) \leq 1 \]

\[ \gamma(x_0, x_i) = \frac{1}{m} \sum_{i=1}^{m} \gamma(x_0(k), x_i(k)) \quad \ldots (8) \]

Where \( \gamma_i(k) \) is the grey relational coefficients. \( \Delta \min \) and \( \Delta \max \) are the minimum and maximum value obtained from deviation sequence. \( \zeta \) is the distinguishing factor which is defined in the range \( 0 \leq \zeta \leq 1 \). The EDM process parameters are equally weighted in this study and therefore \( \zeta = 0.5 \).

\( \gamma(x_0, x_i) \) is the grey relational grade and m is the number of response variables. Based on this study, one can select a combination of the levels that provide the largest average response.

**Results and Discussion**

As shown in Fig. 5 pulse-on time and peak current is directly proportional to MRR and inversely proportional to voltage. While effect of spindle speed upon MRR is negligible. Soni and Chakraverty found similar results because electrode rotation improves the MRR due to improved flushing action and sparking efficiency. In context of surface roughness pulse-on time and peak current are identified as the most dominating parameters which affect sensitivity of the system as shown in Fig. 6. These results are close to results obtained by Gohil and Puri. They reported that high peak current shows greater amount of discharge energy that generates larger and deeper craters on the surface resulting in deterioration of work-piece surface. As similar to the current effect, when the pulse-on time is increased, the amount of heat energy is transferred to the work-piece surface and the more material melted. However, the effect of voltage and spindle speed is less than the other factors.

Polarity is the another important parameter which can be positive or negative. In the present study both straight and reverse polarity is considered. As shown in Fig. 5 material removal is found higher at straight
polarity. However, at reverse polarity EDM turned surface was found more smoother as shown in Fig. 6.

Table 3 shows S/N ratio with its corresponding normalized values for material removal, and surface finish. All these normalized values has been converted into deviation sequence and further into grey relational coefficients using Eqs (6) and (7) as indicated in this paper. As already stated before distinguishing coefficient has been taken as 0.5, as all the process parameters are equally weighted. After getting the grey relational coefficients, grey relational grade has been calculated using Eq. (8). Table 3 shows GRG for all the experiments. The higher the grey relational grade represents that the corresponding experimental result is closer to the ideally normalized value. Experiment 11 has the best multiple performance characteristics because it has the highest grey relational grade, indicating the optimal process parameter set of $A_2B_1C_2D_1E_1$ has the best multiple performance characteristics among the 18 experiments. The mean of grey relational grade for each level of the machining parameters is summarized in Table 4 and shown in Fig. 7. It shows the predicted optimal parameter setting, i.e., polarity at level 2, pulse-on time at level 3, peak current at level 2, voltage at level 1 and spindle speed at level 3 thus optimal parameter combination is $A_2B_3C_2D_1E_3$. In addition the total mean of the grey relational grade for the 18 experiments is also calculated and given in Table 4. The higher delta value indicates the most important nature on determining response in the process. Figure 7 depicts the plot of the mean effect on grey relational grade, and those can be used to graphically assess the effect of the machining parameter on the response characteristics. The steep slope of grey relational grade graph (means plot) indicates the more significance of parameter in the response. It indicates that polarity and peak current have a most significant effect on grey grades, which is supported by the Table 5. Hence it can be concluded that the polarity and peak current is the most influencing factor among all input parameters in EDM turning process. The results of confirmation experiment are compared with the findings of orthogonal array and predicted grey relational grade. As shown in Table 6 MRR is accelerated from 18.195 mg/min to 20.460 mg/min and surface roughness is improved from 2.746 $\mu$m to 2.361 $\mu$m.

**Confirmation experiment**

Once the optimum level of machining parameters is obtained, the final step is to predict and verify the
improvement of the performance characteristics. The results of confirmation experiment are compared with the outcome of the orthogonal array and grey theory prediction of the design operating parameters. The estimated grey relational grade $\gamma_{\text{pred}}$ using the optimal levels of the machining parameters can be computed as:

$$
\gamma_{\text{pred}} = \gamma_m + \sum_{i=1}^{q} (\gamma_i - \gamma_m)
$$

... (9)

Where, $\gamma_m$ is the total mean grey relational grade, $\gamma_i$ is the mean grey relational grade at the optimum level and $q$ is the number of machining parameters.

Conclusions

An application of combined TGRA technique to improve the multi response characteristics of material removal rate and surface roughness in electrical discharge turning of titanium Ti-6Al-4V has been reported in this paper. The optimal process parameters based on grey relational analysis include pulse-on time $T_{on}$ 15 $\mu$s, peak current at 15 A, voltage at 50 V, spindle speed at 100 RPM and negative polarity. Confirmation experimental results show the material rate increases from 18.195 mg/min to 20.460 mg/min and surface roughness decreases from 2.746 $\mu$m to 2.361 $\mu$m. Thus the improvement in MRR and $R_a$ is 1.12 times and 1.16 times, respectively.

References